Statens vegvesen

Durability aspects of fly ash and slag in concrete

Presentations from a Nordic workshop

Statens vegvesens rapporter

Nr. 149

Vegdirektoratet
Trafikksikkerhet, miljø- og teknologiavdelingen
Tunnel og betong
August 2012

Statens vegvesens rapporter

NPRA reports
Norwegian Public Roads Administration

Tittel
Bestandighetsaspekter ved bruk av flygeaske og slagg i betong

Undertittel
Presentasjoner fra Nordisk workshop

Forfatter
Bård Pedersen (redaktør)

Avdeling
Trafikksikkerhet, miljø- og teknologiavdelingen

Seksjon
Tunnel og betong

Prosjektnummer
601762

Rapportnummer
Nr. 149

Prosjektleder
Bård Pedersen

Godkjent av
Claus K. Larsen

Emneord
Bestandighet, betong, tilsetningsmaterialer, flygeaske, slagg

Sammendrag
Rapporten er en sammenstilling av 23 presentasjoner fra Nordisk workshop/ miniseminar "Durability aspects of fly ash and slag" avholdt i Oslo 15. og 16. februar 2012.

Antall sider 307

Dato 2012-08-07

Title
Durability aspects of fly ash and slag in concrete

Subtitle
Presentations from a Nordic workshop

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Section
Tunnel and concrete

Project number
601762

Report number
No. 149

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Key words
Concrete durability, supplementary cementing materials, fly ash, blast furnace slag

Summary
This publication contains 23 presentations given at the Nordic Workshop/ Mini Seminar "Durability aspects of fly ash and slag in concrete" held in Oslo on February 15 and 16, 2012.

Pages 307

Date 2012-08-07

PREFACE

The workshop

This publication contains **23 presentations** given at the Nordic Workshop/ Mini Seminar "Durability aspects of fly ash and slag in concrete" held in Oslo on February 15 and 16, 2012. The **papers** written in connection to this workshop are published separately as Publication number 10 in a special series of Workshop-Proceedings of the Nordic Concrete Research.

The workshop was organised by Bård Pedersen and Claus K. Larsen from the Norwegian Public Roads Administration & Dirch H. Bager, DHB-Consult.

Nordic Mini Seminars are workshops arranged solely for researchers from the Nordic Countries in order to strengthen the inter-Nordic co-operation. A few foreign specialists can however be invited. To further stimulate discussions, only participants actively contributing are invited. 75 such Mini Seminars have been held since 1975.

38 researchers from Denmark, Finland, Iceland, Norway, Sweden, Canada, the Netherlands, Germany and UK participated in this workshop.

Background and motivation for our initiative

Having more than 10 000 concrete bridges, more than 1000 tunnels and many ferry quays in service, many of these along the long Norwegian coastline with very harsh climate, we have a strong interest in every aspect of concrete durability. Historically, Norwegian concrete bridges were built using Portland cement concrete. From approximately 1989 all bridges have been built with a maximum water/binder ratio of 0.40 and with addition of minimum 4 % silica fume. The major durability concern for concrete bridges built before 1989 is reinforcement corrosion due to a combination of insufficient rebar cover and insufficient chloride resistance of the concrete. In addition, many of the older structures suffer from alkali-silica reactions. However, problems associated with freeze-thaw resistance are rarely seen on Norwegian bridges.

During the latest decade, blended cements have become dominating on the Norwegian market. The most common cement type is now CEM II/A-V containing 17-20 % fly ash, while higher fly ash addition levels up to approximately 40 % have been used for special projects. Slag is less common than fly ash in Norway, but there is CEM II/B-S with 33 % slag available on the Norwegian market.

The NPRA have been performing rather extensive research and documentation programs on low-to-high volume fly ash and slag concrete during the latest decade. Some of the NPRA results with relevance for rebar corrosion were presented by Claus K. Larsen during the workshop. Fly ash addition levels up to 40 % have been used with great success for massive infrastructures in order to reduce the heat generated by hydration and thus the cracking sensitivity, as presented at this workshop by Øyvind Bjøntegaard.

Some of the positive effects of using blended cements with fly ash or slag include reduced chloride penetration rates, increased electrical resistivity, mitigating effect against alkali-silica reactions, improved sulphate resistance and reduced heat of hydration. However, there are some concerns or question marks, in particular when going to very high addition levels of fly ash or slag.

Some of the questions raised by the NPRA are shown below:

- Frost/salt (scaling) resistance. Historically, few frost problems on Norwegian highway structures. Are we creating new problems if we start using high-volume fly ash/slag applications?
- Excellent long term chloride ingress performance, but what about the early age resistance against chloride ingress? High volume fly ash concrete is slow and strongly temperature dependent.
- How do blended cements affect the critical chloride content for depassivation of steel?
- What about carbonation, is the increased carbonation rates for blended cements of significance for high performance concrete?
- We have observed very high levels of long-term electrical resistivity for FA-concretes. What are the practical consequences of this with respect to corrosion rates?
- What about self-healing of cracks? We have seen indications on lower, or at least slower self-healing of cracks.
- ASR: Norwegian regulations are based on laboratory performance testing. Does the combination of reactive aggregates, high alkali levels and low fly ash addition levels give a sufficient safety level?

Based on our general interest in blended cements with fly ash and slag, and our concerns listed above, we took the initiative to arrange the workshop. Our intention with this was to gain more updated information from the international community and to stimulate to cooperation and further research on the issues needing more attention.

What did we learn?

It is hardly possible to summarize a two-day workshop on a few pages, but in the following some important issues are highlighted.

- One important lesson learnt is that the practice for making durable concrete structures differs a lot from country to country. This is due to variations in climatic condition, variations in cement composition, variations in access to supplementary materials, different national rules and regulations and differences in concrete technology traditions. As an example of this, there is a striking difference between the Dutch practice of using CEM III/B with approximately 65-70 % slag for marine structures and the Swedish traditions using a low alkali sulphate resistance CEM I for infrastructures.
- There are obviously large differences in chemical and mineralogical composition for fly ash and slag from different sources, and it is therefore difficult to generalize. The performance of a given supplementary material in combination with a given Portland cement is generally difficult to predict based on its composition, and the real performance should always be verified.

- Slag cements generally seem to develop a dense pore structure at relatively early ages, while fly ash cement is a lot slower (with a larger temperature dependency). Early age exposure to chlorides may therefore be a critical factor for (high volume) fly ash concrete.

- Fly ash addition levels from approximately 20 % or higher or slag addition levels from approximately 50 % seem to give a fairly good ASR-mitigating effect. However the effect depends strongly on the type of reactive rock, the cement alkali level as well as the chemical composition of the fly ash or slag. More reliable tools for "performance testing" of any given mix design are being developed.

- Ternary blends including silica fume may improve the early age properties significantly compared to binary blends. There also seem to be a long term "synergistic effect" from ternary blends with respect to ASR-mitigation.

- In general, fly ash and slag cause increased carbonation rates. Even though depassivation of steel due to carbonation may not be relevant for high performance concrete with large cover depths, carbonation may negatively affect other properties such as frost/salt resistance and chloride penetration rates.

- High volumes of fly ash and slag may cause a negative effect on frost/salt resistance. Generally, it seems more difficult to attain a sufficient quality of the air pore structure in the presence of fly ash or slag. In addition, the effect of entrained air with respect to frost/salt resistance seems somewhat unclear. There seems to be a general need to calibrate laboratory performance versus real field behaviour.

- The effect on critical chloride content is still unclear, and needs more attention.

- Addition of fly ash and slag generally increases the electrical resistivity of concrete, which again reduces the corrosion rates. Further research to quantify these effects is in progress.

- Blended cements (in particular high volume fly ash cements) may give a significant reduction in heat of hydration, consequently "crack-free" structures are easier to achieve. On the other hand, blended cements may reduce the self-healing abilities, or at least slow down the self-healing processes.

We consider workshops of this kind to be an excellent meeting-place to exchange and discuss research results, to identify needs for further research and to initiate partnership for future research collaboration. In this respect, the workshop was successful and very useful for the NPRA and we trust also for the other participants.

Bergen, July 2012

Bård Pedersen

CONTENTS:

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Fly Ash – An Overview of its Production, Properties and Utilisation in Europe

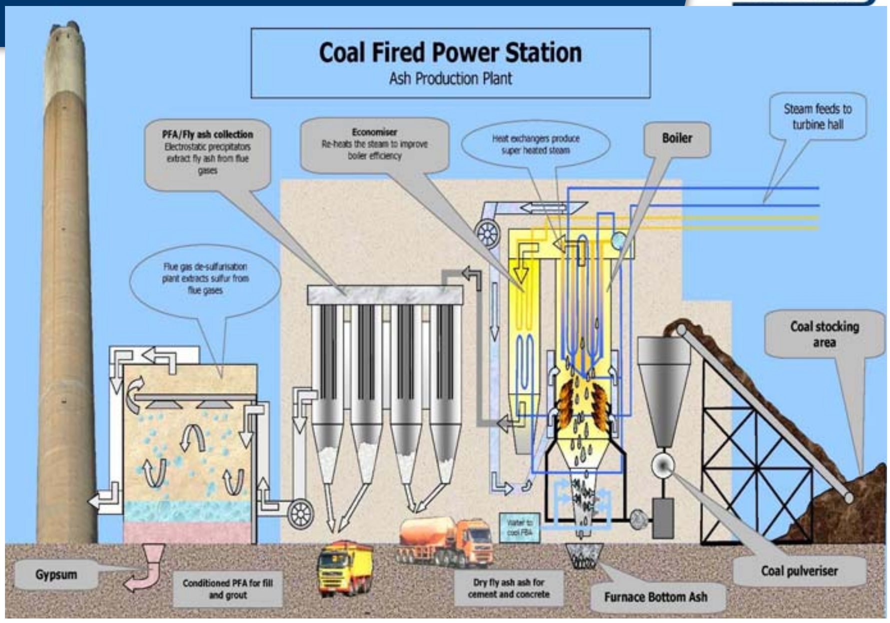
Peter Brennan
Nordic Workshop - 15.02.2012

steag

What is the presentation about?

steag

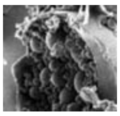
- **How fly ash is produced within coal-fired power stations.**
- **The basic properties of fly ash.**
- **The main markets into which fly ash can be sold.**
- **The current position in Europe regarding utilisation of fly ash.**
- **A basic overview of the use of fly ash in concrete together with examples of its use.**

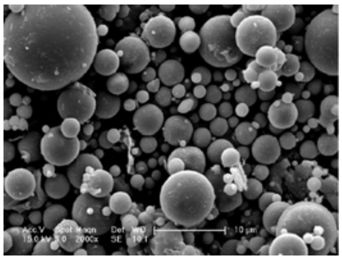


The Physical Nature of Fly Ash

PFA particles <45µm are predominantly spherical in nature:

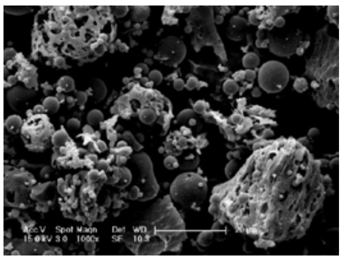
- **They are glass spheres.**
- **Hollow spheres are known as cenospheres – they float on water.**





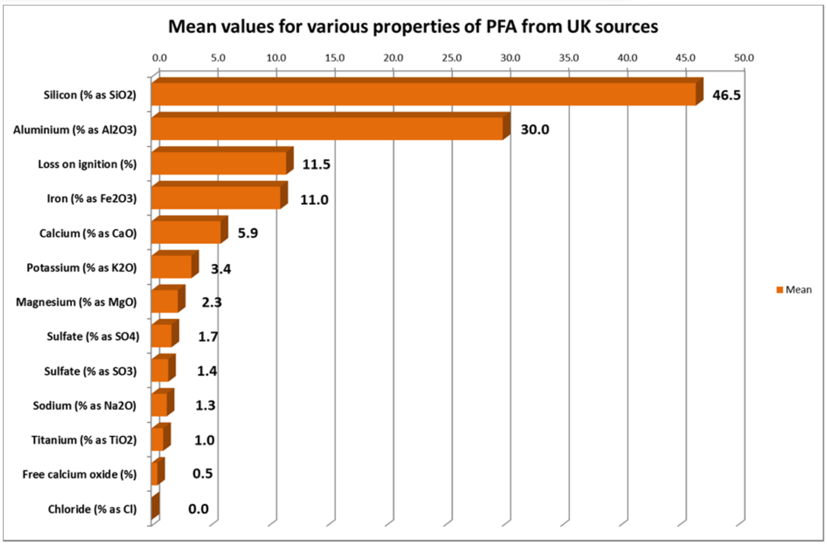
Coarser particles are more irregular:

- **Carbon particles are like charcoal – they can vary in size and shape.**



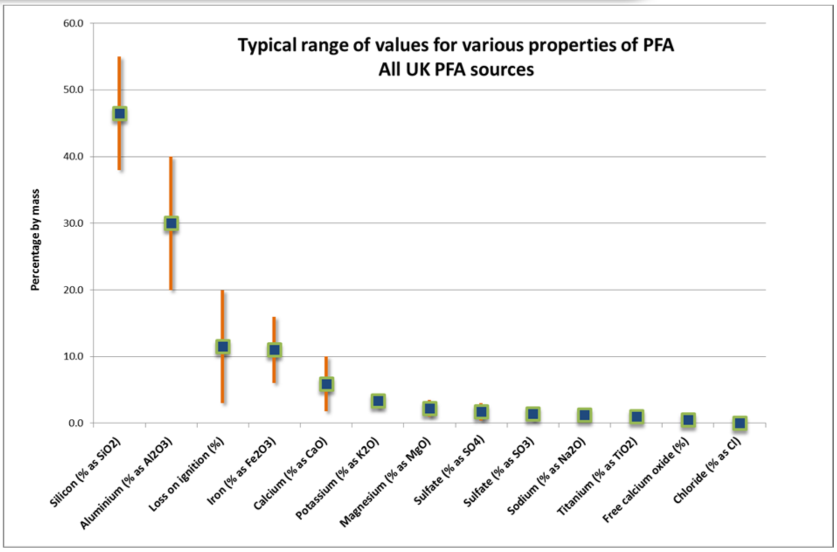
The Chemical Properties of Fly Ash

steag



The Range of Properties of Fly Ash

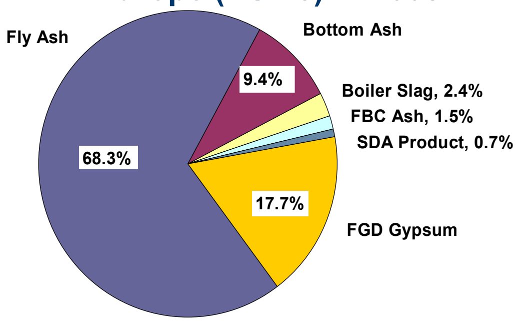
steag



Principal Markets for Fly Ash

- Cement manufacture
- Ready-mix concrete
- Concrete products
- Autoclaved Aerated Concrete Blocks
- Engineered Fill – e.g. road embankments, bridge abutments
- Grouting – e.g. filling underground voids and mine workings

Production of Coal Combustion Products (CCPs) in Europe (EU 15) in 2008



- ► Production of CCPs in Europe (EU15) is approximately 60 million tonnes per annum
- ► Total production of CCPs in EU 27 is estimated to be more than 100 million tonnes per annum

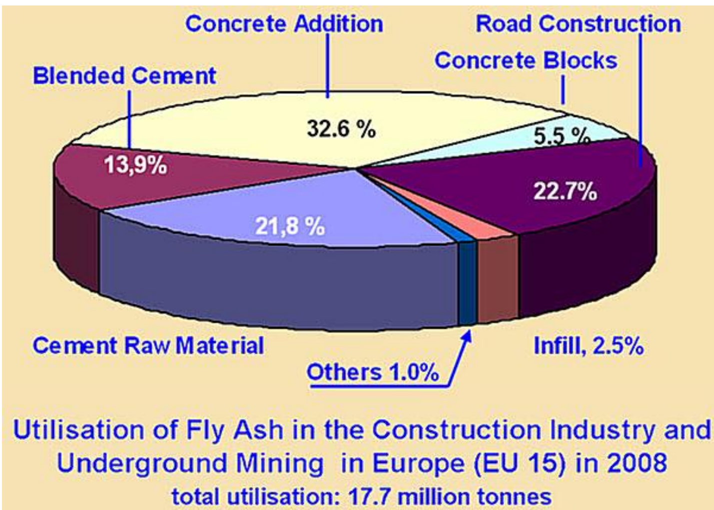
Fly Ash production (EU15)

steag

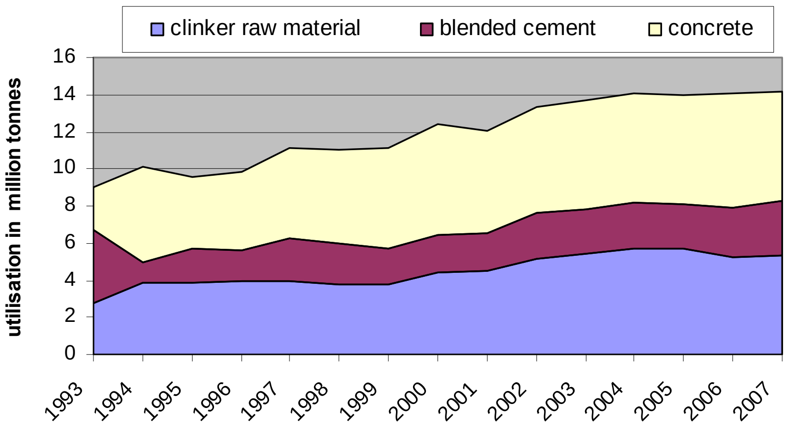
- Hard coal Fly Ash production in the EU 15 region is estimated with approximately 33 million tonnes per annum
- This figure includes qualities which are not suitable for the cementitious market (e.g. fluidised bed ashes)

Fly Ash Utilisation (EU15) in 2008

steag



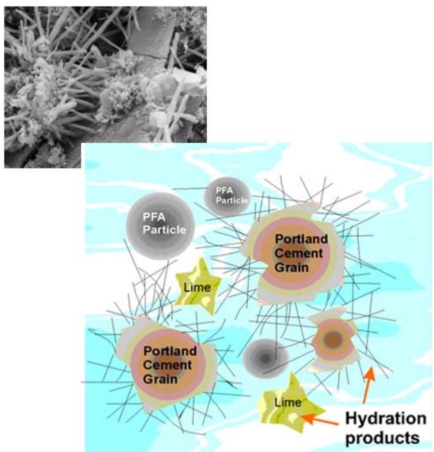
Fly Ash Utilisation in Cement and Concrete (1993 to 2007)

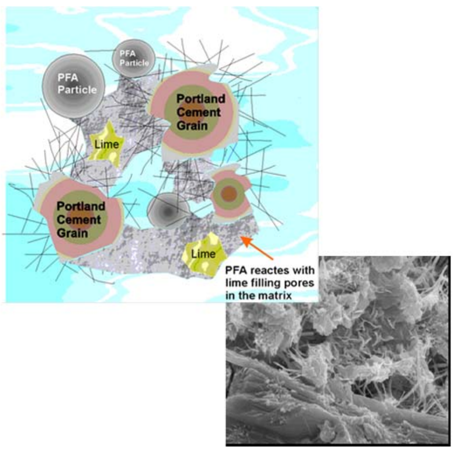


Development of the use of fly ash in cement and concrete in EU 15 countries from 1993 to 2007

Hydration of Fly Ash

Fly Ash reacts with the lime produced by the hydration of cement to give more hydration products - reducing the voids and lowering the permeability. This is the pozzolanic reaction.

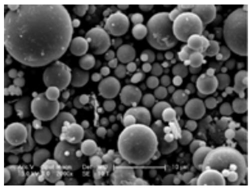




The Benefits of Using of Fly Ash in Concrete

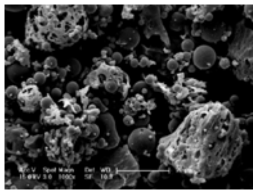
steag

Due to its pozzolanic properties fly ash reacts with lime to form silicate hydrates - these hydrates give concrete its enhanced strength and durability.



In addition the use of fly ash in concrete has the following benefits:

- **Reduced permeability**
- **Improved sulphate resistance**
- **Reduced heat of hydration**
- **Improved workability**



The Use of Fly Ash in Concrete

steag

Fly ash can be used in many ways in concrete.

The following are the main approaches:

As a cement - EN197 and EN14216

Factory made blends of Portland cement and fly ash

As a filler aggregate

EN12620 Aggregates for concrete

EN13055-1 Lightweight aggregates for concrete

As a Type II addition - EN450:2005

March 2005 – harmonized version published (currently under revision).

Mixer blended fly ash for concrete.

Fly Ash Production versus Demand

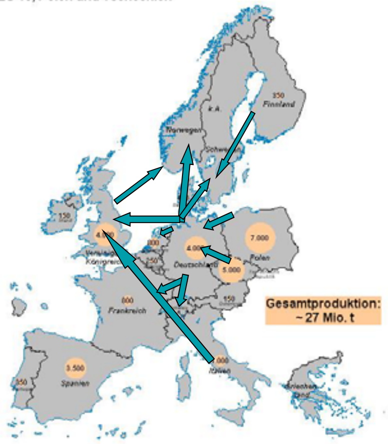
At present in Europe there is a mismatch between areas in which fly ash is produced and areas in which fly ash is required . There is also a seasonal mismatch (winter to summer) between demand and availability of fly ash in some countries.

In response to these challenges the following measures have been introduced:

- Development of international (cross border) sales of fly ash.
- Investment in ash beneficiation technology.
- Investment in silo plants and terminals.
- Exploring the use of conditioned and stockpiled ash.

Note the impact of new coal-fired power stations currently under construction.

Prognose der Flugascheproduktion (Steinkohle) 2016 in [kt]
EU 15, Polen und Tschechien*



Montag, 9. Juli 2012 Fußzeilentext

*Tschechien: Hartbraunkohle

Example 1 : Quality improvement (fly ash beneficiation)

Ash beneficiation at Rugeley Power Station, UK

- Only facility of its kind.
- Reduces LOI content of fly ash by approximately 50%
- Product: fly ash complying with EN 450
- Capacity: 20.000 p.a.
- Capacity can easily be scaled up by means of replication

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Example 2 : Silo facilities

steag

Silo plants:	
Ottmarsheim	**7.700 m³**
Nürnberg	**2.500 m³**
Bachmann	**16.000 m³**
Werne	**4.000 m³**
Neumarkt	**40.000 m³**
Neubeckum	**23.000 m³**
Others:	
Flat store Baums	**18.000 m³**
Redrying plant	**100.000 m³**
Total	**> 200,000 m³**

Fußzeilentext

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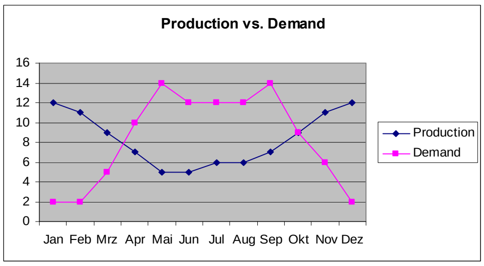
Example 3 : Use of Conditioned and Stockpiled Fly Ash - Redrying Plant in Lünen, Germany

steag

- **Only facility of its kind**
- **Product: fly ash complying with EN 450**
- **Capacity: 100,000 m³**
- **Permit according to the waste legislation, certified recycling plant**
- **Material can be accepted from all over Europe**



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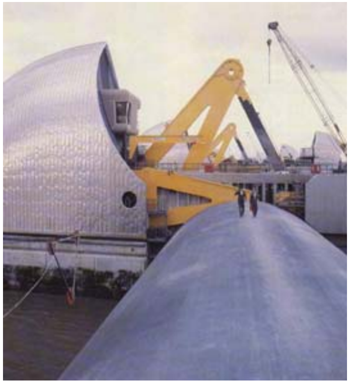
Examples of the Use of EN450 Fly Ash in UK Construction Projects

steag



EN450-1 Fly Ash has been used in many important projects in the UK, from the Thames barrier to Canary Wharf...

Examples of the Use of EN450 Fly Ash in UK Construction Projects

steag

… from self compacting concrete to wind farms …

Examples of the Use of EN450 Fly Ash in UK Construction Projects

steag

…. to Heathrow Terminal 5 to sewage treatment plants…

Examples of the Use of EN450 Fly Ash in UK Construction Projects

steag

…. to the Channel Tunnel Rail Link ...

09.07.2012 | Evonik Power Minerals

Examples of the Use of EN450 Fly Ash in UK Construction Projects

… to Pavement Quality Concrete for airport taxiways and runways.

Joost Gulikers
Rijkswaterstaat
Centre for Infrastructure
Utrecht, The Netherlands

Experiences with the use of blast furnace slag cement concrete at Rijkswaterstaat

February 15-16, 2012

OVERVIEW

- BACKGROUNDS
- BENEFITS OF BLAST FURNACE SLAG CEMENT CONCRETE
- SOME MARINE PROJECTS
- PERFORMANCE SPECIFICATIONS
- CONCERNS

2 Rijkswaterstaat
Nordic Workshop - Oslo February 15-16, 2012

BACKGROUND

EUROCODE:
- all cements are equal

RIJKSWATERSTAAT:
- but some cements are more equal

↓

blast furnace slag cement

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RIJKSWATERSTAAT GUIDELINE (ROK)

EUROCODE IS OK PROVIDED THAT:

READY MIX CONCRETE:
- CEM III > 50% blast furnace slag

PREFAB CONCRETE ELEMENTS:
- CEM III > 50% blast furnace slag
- CEM I + > 25% fly ash

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MOTIVES

- MANAGER OF INFRASTRUCTURE
- DESIGN SERVICE LIFE: 100yr
- ZERO MAINTENANCE
- DURABILITY
- SUSTAINABILITY

BENEFITS OF CEM III / CEM II B-V

- LOW PERMEABILITY
- ALKALI SILICATE REACTION
- HIGH SULFATE RESISTANCE
- LOW HEAT OF HYDRATION
- REDUCTION OF CO_2 EMISSION

THE NETHERLANDS – SOME PROJECTS

7 Rijkswaterstaat
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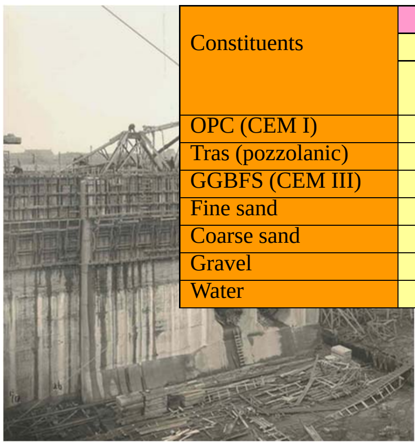
NOORDERSLUIS – IJMUIDEN 1921-1929



Constituents	Typical Mix Design			
	Lock head		**Chamber walls and floors**	
	Liter	Ratio (V/V)	Liters	Ratio (V/V)
OPC (CEM I)	225	1		
Tras (pozzolanic)	56	¼		
GGBFS (CEM III)	--	--	240	1 1/8
Fine sand	193	0,85	193	0,9
Coarse sand	387	1,7	387	1,8
Gravel	700	3,1	700	3,3
Water	??	??	??	??

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Nordic Workshop - Oslo February 15-16, 2012

NOORDERSLUIS - PRESENT CONDITION

NO SERIOUS DEGRADATION

9 Rijkswaterstaat
Nordic Workshop - Oslo February 15-16, 2012

ALKALI SILICA REACTION

10 Rijkswaterstaat
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DELTA PROJECT

11 Rijkswaterstaat
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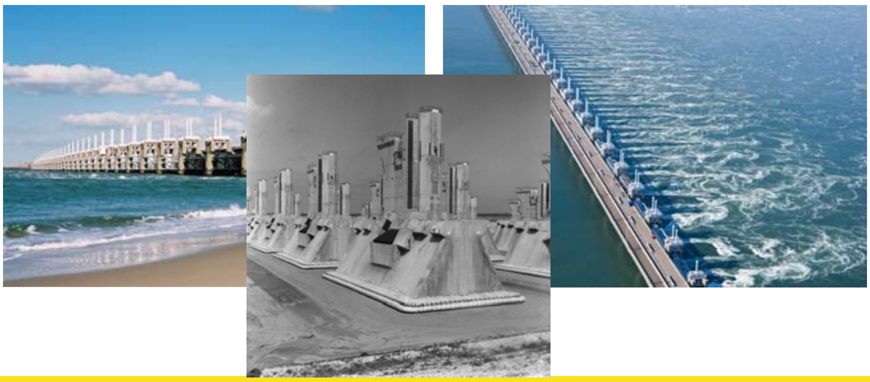
EASTERN SCHELDT STORM SURGE BARRIER (1)



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EASTERN SCHELDT STORM SURGE BARRIER (2)

- Piers, upper and lower beams: 200 years
- Bridge structure: 50 years
- Marine environment

→ Chloride-induced reinforcement corrosion

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HARINGVLIET DISCHARGE SLUICES

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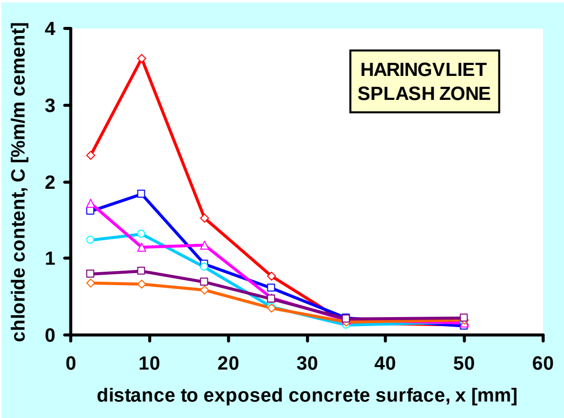
HARINGVLIET – CHLORIDE PROFILES



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CARBONATION & FROST-THAW

- CEM III/B: MORE SENTIVE TO CURING
- CARBONATION: NO PROBLEM
- LAST 3 YEARS: (RELATIVELY) SEVERE WINTERS
- DAMAGE TO UPSTANDS
- CAUSE: POOR CURING

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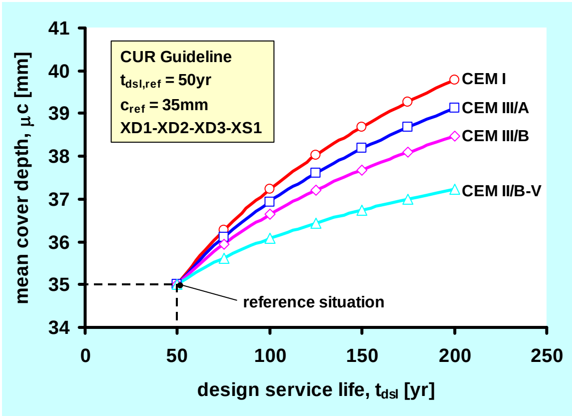
PERFORMANCE-BASED APPROACH



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CONCERNS

- EXPERIENCE IS BASED ON 'DUTCH' SLAG GLASS CONTENT > 95%
- PROPER EXECUTION AND CURING REQUIRED
- TOO MUCH FOCUS ON (MATHEMATICAL) MODELLING AND LABORATORY TEST METHODS

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AN ADDITONAL ADVANTAGE

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Rijkswaterstaat
Nordic Workshop - Oslo

February 15-16, 2012

DHB-Consult

The k-value concept

Equivalent Performance of Combinations Concept

Equivalent Concrete Performance Concept

Dirch H. Bager

DHB-Consult

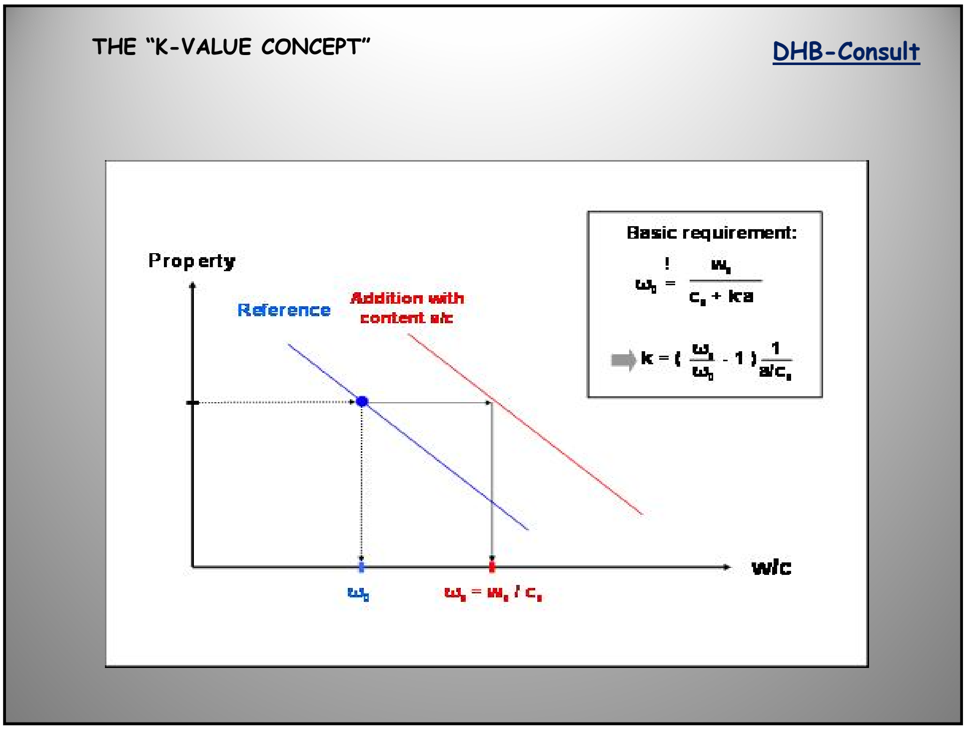
Oslo 2012-02-15

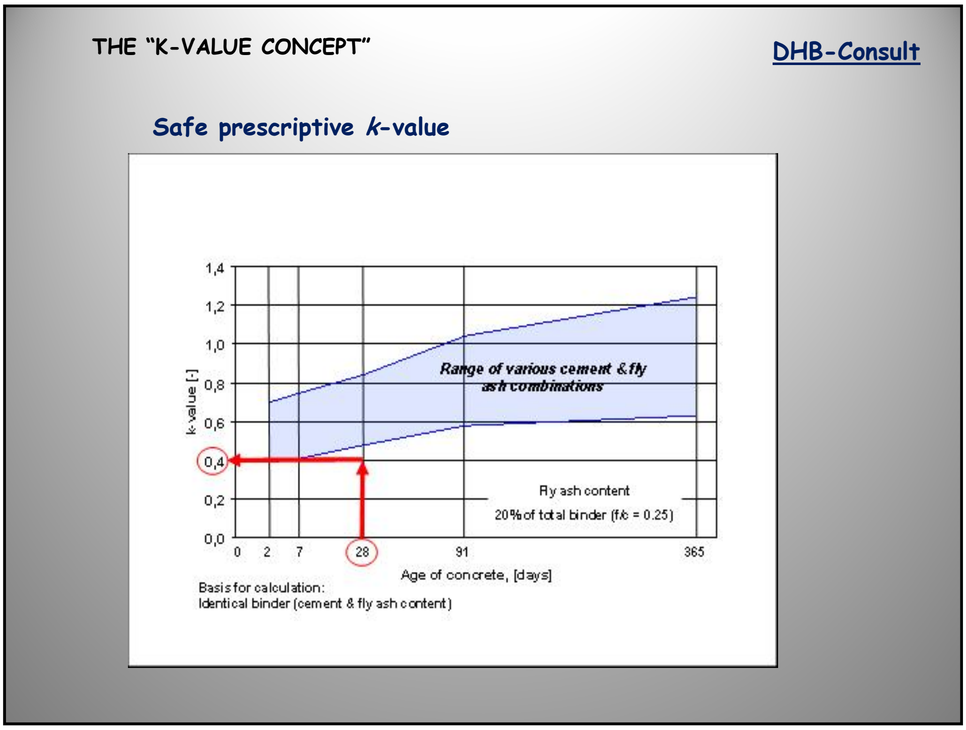
THE "K-VALUE CONCEPT"

DHB-Consult

The k-value concept is a prescriptive concept which is based on the comparison of the performance
(durability or strength as a proxy-criterion for durability where appropriate)

The k-value concept permits type II additions to be taken into account
by replacing the term "water/cement ratio"
with "water/(cement + k * addition) ratio"


THE "K-VALUE CONCEPT"
DHB-Consult
Basic requirement:
Property
Reference
Addition with content a/c
w/c


THE "K-VALUE CONCEPT"
DHB-Consult
Safe prescriptive k-value
Range of various cement & fly ash combinations
k-value [-]
Fly ash content
20% of total binder (f/b = 0.25)
Age of concrete, [days]
Basis for calculation:
Identical binder (cement & fly ash content)

THE "K-VALUE CONCEPT"

DHB-Consult

EN 206-1:2000	prEN206:2011
CEM I	CEM I & CEM II/A
k_{FA} = 0.4 k_{MS} = 2 / 1	k_{FA} = 0.4 k_{MS} = 2 / 1 k_{GGBFS} = 0.6

- Safe, lower level
- Can be applied without testing
- Specific values, cements, conditions shall be well defined in EN 206-1 and NAD's

THE "K-VALUE CONCEPT"

DHB-Consult

Country	Product	k-value	Comments
Denmark	FA (Category A)	0.5	CEM I, CEM II/A-L, CEM II/A-LL
	MS (Class I & II)	2.0	CEM I, CEM II/A-L, CEM II/A-LL, CEM II/A-V, CEM II/B-V.
	GGBFS	-	Not accepted for use
Finland	FA	0.4	CEM I, CEM II/A-S, CEM II/A-D, CEM II/A-V, CEM II/A-LL, CEM II/A-M, CEM II/B-S, CEM II/B-V, CEM II/B-M, CEM III/A, CEM III/B.
	MS	1.0/2.0	
	GGBFS	0.8 1.0 in XA	Additions included in the cement are taken into account as type II addition in the concrete
Iceland	FA		
	MS		
	GGBFS		
Norway	FA	0.2/0.4	CEM I
	MS	1.0/2.0	CEM I, CEM II/A-S, CEM II/B-S, CEM II/A-D, CEM II/A-V, CEM II/B-V and CEM III/A dependent on exposure class
	GGBFS	0.6	CEM I, CEM II/A-L, CEM II/A-S, CEM II/B-S, CEM II/A-D, CEM II/A-V, CEM II/B-V and CEM III/A
Sweden	FA	0.4	CEM I and CEM II
	MS	1.0/2.0	
	GGBFS	0.6	

DHB-Consult

Equivalent Performance of Combinations Concept - EPCC

- An addition added at the concrete mixer may be considered to perform in concrete in the same way as the same addition added at a cement factory.
- A continuous programme of control testing of the specific addition with the specific cement, has to be carried out
- Applied in the UK, Portugal, NL …

EPCC

DHB-Consult

- Restricted to cement and addition from specific sources
- Restricted to Portland cement CEM I 42,5 and 52,5
- Monthly testing of samples and statistical evaluation of the strength class of the combination addition taken into account in the same way as if it were a constituent in the cement

EPCC

DHB-Consult

Rules for use of combinations

- The combination counts fully towards the cement content and water/cement ratio in concrete
- Combinations are used in concrete in the same way as cements of the same composition and strength class

EPCC

DHB-Consult

UK terminology

CEM II /A-V

→

C II/A-V

DHB-Consult

EQUIVALENT CONCRETE PERFORMANCE CONCEPT ECPC

ECPC

DHB-Consult

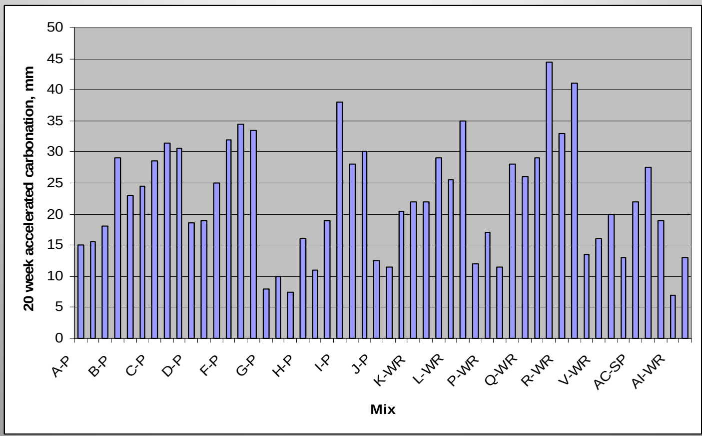
Background

- Survey of national provisions used with EN 206-1
  - Significant variations for the same exposure class
  - Impact of aggregates are ignored (at least in a direct way)
- National provisions do not lead to the same performance

ECPC

DHB-Consult

Background



Example of the range of carbonation resistances achieved with concrete conforming to a maximum w/c ratio of 0.55, minimum cement content of 300 kg/m^3 and compressive strength of at least 40 MPa

ECPC

DHB-Consult

Principles

- Reference concretes are selected on basis of long-term good track record in the local environment
- Candidate concrete is designed and tested to show that it has equivalent durability
- Assumption that this candidate concrete will give an equivalent performance in practice

ECPC

DHB-Consult

Principles

- Candidate concrete has to be made with constituents conforming to European standards or provisions valid in the place of use
- Candidate concrete has no 'limiting values'
- Effects of execution of construction assumed to be the same
- Third party certification

ECPC

DHB-Consult

Principles

- In theory the procedure could be applied to any exposure class, but in practice it is limited to exposure classes where there are the necessary tools, i.e. test methods and procedures
- Current work is focusing on XC, XD, XF and XS exposure classes
- Uncertainty of measurement taken into account

ECPC

DHB-Consult

Reference concretes

- Guidance will be provided, but national selection
- Prescribed concrete
- W/C ratio 0.02 less than the maximum for the exposure class
- All constituents, including aggregates, have to be clearly specified

ECPC

DHB-Consult

Approach for XC exposures

- Applies to XC3 and XC4
- Depending on local interpretation, it may apply to XC1 and XC2
- Comparison based on 10 week accelerated carbonation test
- Test procedure being standardized by CEN/TC51(CEN/TC104)/JWG12/TG5

ECPC DHB-Consult

Approach for XD/XS exposures

- Chloride diffusion test going for formal vote as TS
- Problems with calculating diffusion coefficient in high quality concrete in relatively short test (90 days)
- Diffusion coefficients change with time but not in uniform way
- Ageing factor needed

ECPC DHB-Consult

Approach for XD/XS exposures

- Alternative approach based on rapid migration test being considered
- This test is quick, easy and not too expensive to undertake
- After three months the test result does not change significantly

ECPC

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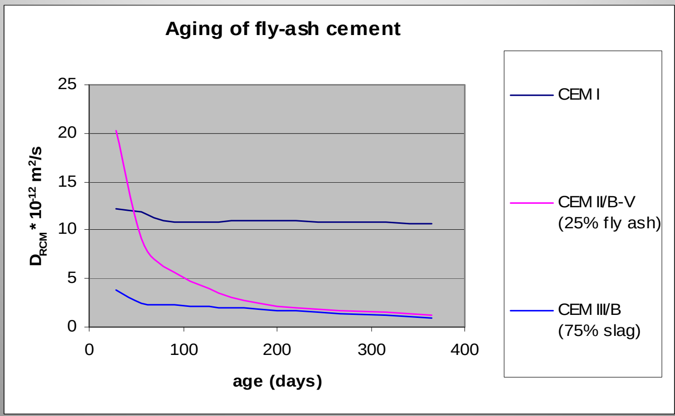
Rapid migration test



ECPC

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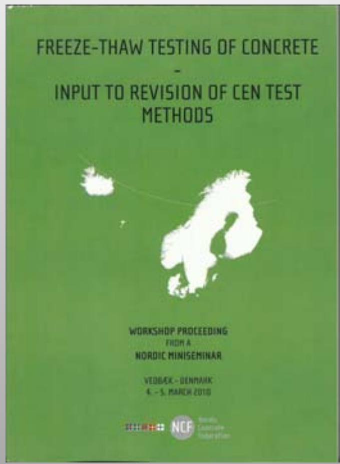
Approach for XF exposures

- TS 12390-9 are severe tests that may be used to specify performance directly
- May fail concretes that have a long service record in practice
- CEN/TC51(CEN/TC104)/JWG12 have been asked to develop a less severe relative test
- Will it be available in time?

ECPC

DHB-Consult

Approach for XF exposures



Input to CEN/TC51(CEN/TC104)/JWG12/TG 4 on frost test methods.
Nordic participants: Terje F. Rønning, Peter Utgennant, Dirch H. Bager

ECPC

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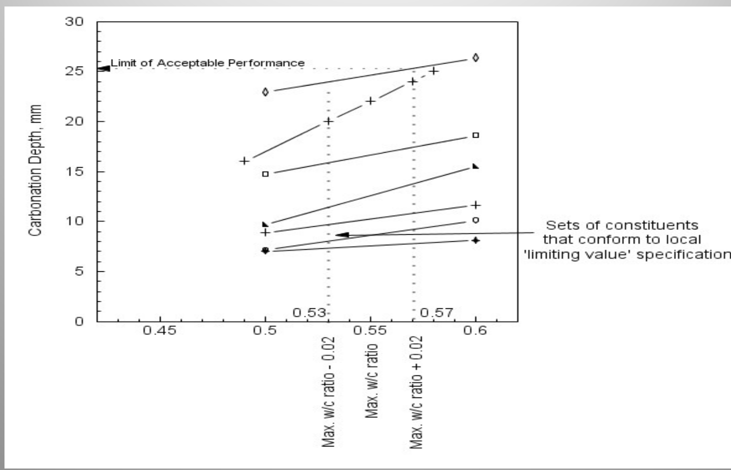
Production control

- Based on batch records plus the control of strength given by the candidate concrete
- Changes that have an adverse effect on strength are assumed to have an adverse effect on durability
- Not all changes that have an adverse effect on strength have an adverse effect on durability, but safe assumption
- Periodic confirmation of performance

ECPC

DHB-Consult

Issues: Reference concrete



ECPC

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Issues: Uncertainty of measurement

- Precision of test methods not fully established
- More than one test specimen may be needed to gain adequate precision
- Aim is to have precision data for all test methods and then upgrade from TS to EN

ECPC

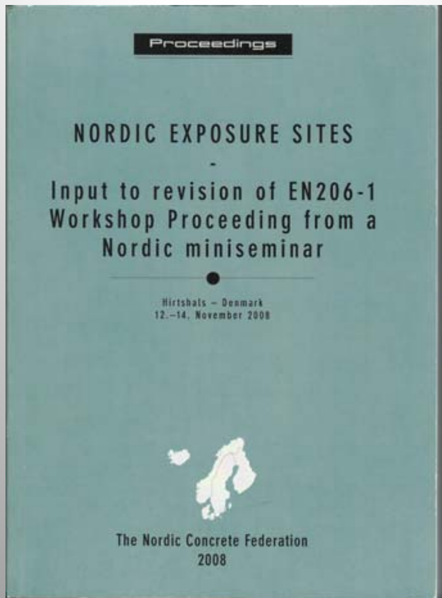
DHB-Consult

Issues: Ageing effect

- ❑Procedure has to be established
- ❑Will be based on cement or cement/addition type
- ❑Lack of data

ECPC

DHB-Consult



Input to CEN TC 104 / SC 1 / TG 17

DHB-Consult

Conclusions:
EN 206-1:2000 ➔ prEN 206:2011

The k-value concept

Unaltered + recommended k-value for GGBFS

Equivalent Performance of Combinations Concept

Incorporated.

A CEN TR will provide more detailed information

Use of EPCC to be decided nationally

Equivalent Concrete Performance Concept

Replaces annex E

A CEN TR will provide more detailed information

Use of ECPC to be decided nationally

ISO 16204
Service Life Design of Concrete Structures

Nordic Workshop
on
Durability aspects of fly ash and slag in concrete

Oslo, February 15th, 2012

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Steinar Helland

1

Service life design

According to most national and regional building legislation, the construction team are obliged to verify a certain service life of the new structure

As engineers we must predict the performance of our structures after 50, 100 or more years

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In some rare cases we can relay on long-term experience

Bridge at castle of Chazelet, French alps

Joseph Monier - 1875

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Deemed-to-satisfy requirements in Europe

European Standards EN 206 / EN 1992 / EN 13670 require the 31 member-nations to give provisions for 50 yrs service life based on:

- w/c
- Cement type
- Strength and/or min amount of cement
- Cover to the reinforcement

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Deemed-to-satisfy requirements in Europe (50 year service life)

Range of XC3 provisions for Portland Cement, CEM I (carbonation, moderate moisture)

UK → w/c < 0.55 and 25 mm minimum cover

DE → w/c < 0.65 and 20 mm minimum cover

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Deemed-to-satisfy requirements in Europe (50 year service life)

Range of XS2 provisions for CEM I (submerged in sea-water)

UK → w/c < 0.50 and 35 mm minimum cover

NO → w/c < 0.40 (+ silica fume) and 40 mm minimum cover

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Why are the differences in recommendation from different groups of experts so great ??

Let us look into the basics in degredation of concrete structures

Basics:

Environmental load

versus

Structural resistance

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EN 206-1 & ISO 22965-1, Exposure classes

1. No risk of corrosion or attack	
XO	Without reinforcement or with reinforcement, but very dry
2. Corrosion induced by carbonation	
XC1	Dry or permanently wet
XC2	Wet, rarely dry
XC3	Moderate humidity Cyclic wet and dry

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Environmental load on the structure

Chlorides from sea-water

North Sea platforms for oil exploration

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Oseberg A

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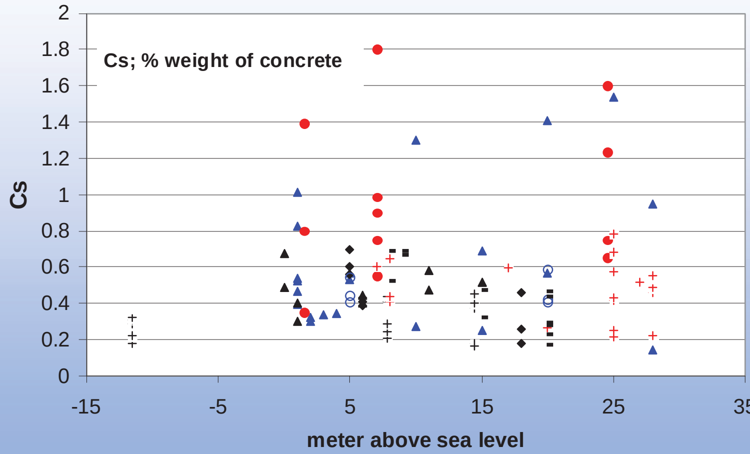
Surface chloride concentration, Cs, versus height above sea level



Also in this case the severity of the environmental and depens on the meso- and micro-climate

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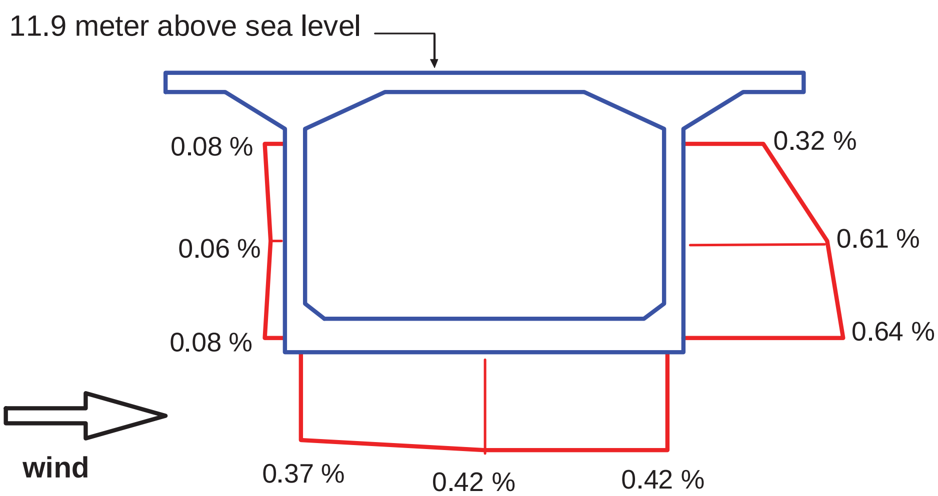
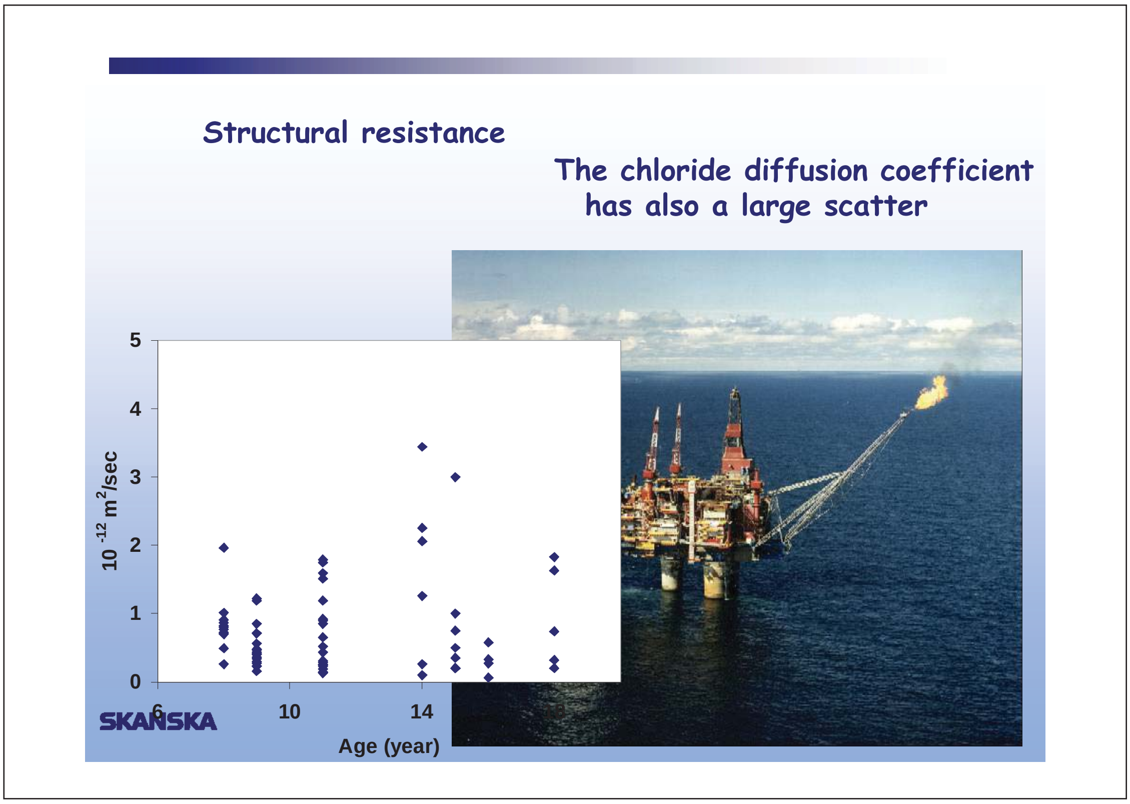
SKANSKA Gimsøystraumen, Norway 11

Gimsøystraumen bridge

Cs - Surface chloride concentration (% of concrete)




Structural resistance
The chloride diffusion coefficient has also a large scatter
5
4
3
2
1
0
10 -12 m2/sec
6
10
14
Age (year)
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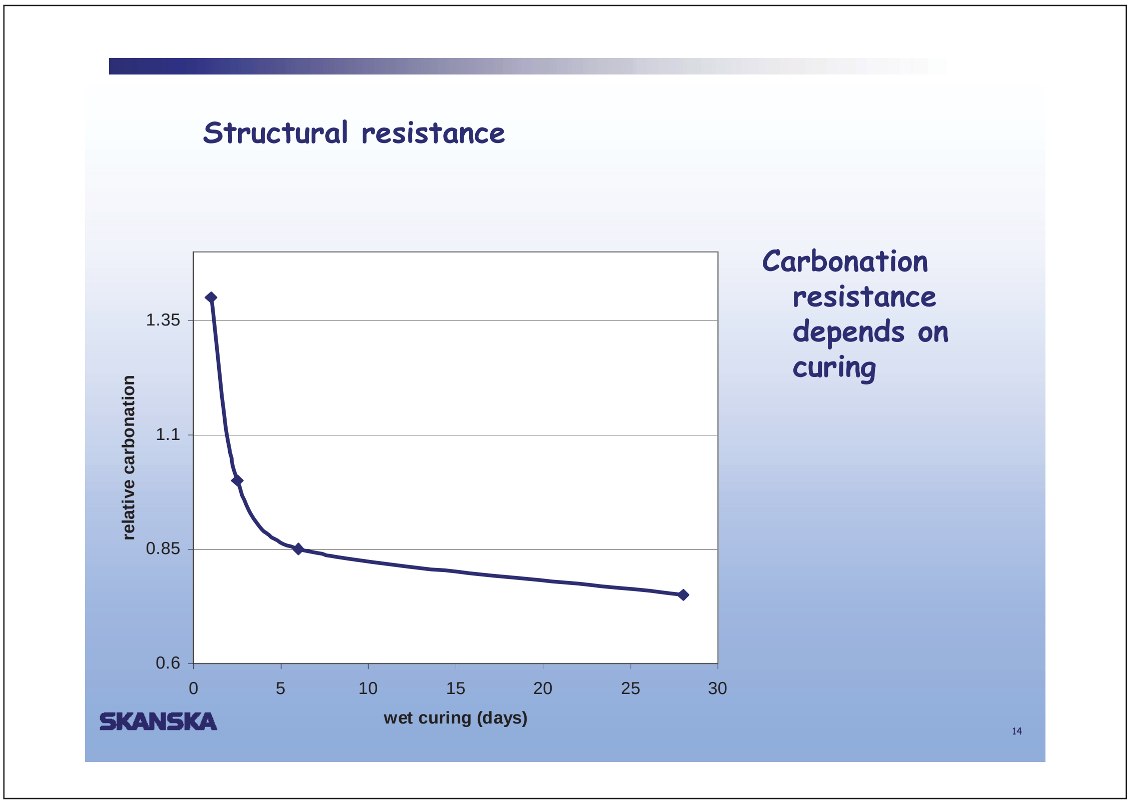
Structural resistance
Carbonation resistance depends on curing
1.35
1.1
0.85
0.6
relative carbonation
0
5
10
15
20
25
30
wet curing (days)
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Structural resistance

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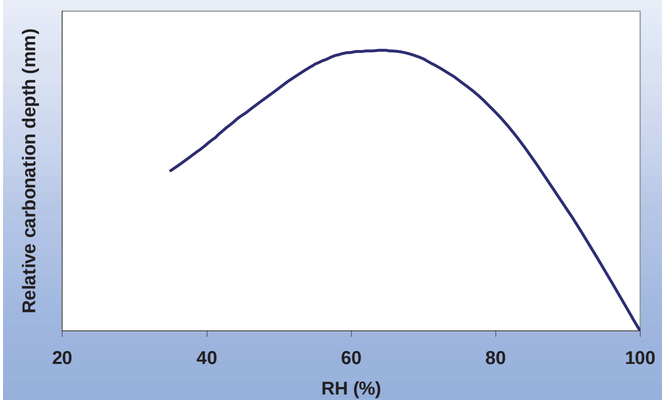
Environmental load on the structure

Carbonation rate is heavily influenced by the humidity



For a particular structure, or structural member, the severity of the environmental load depends on the meso- and micro-climatic conditions

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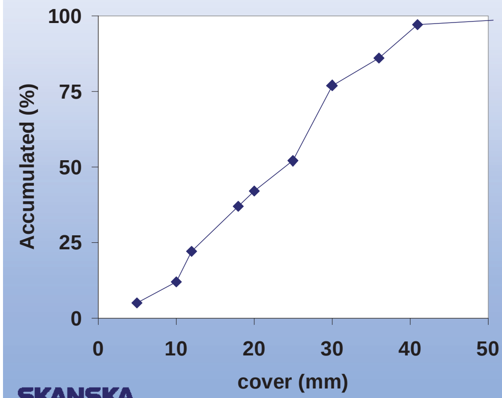
Structural resistance

Depends on the actual concrete cover



Example from a residential complex in Oslo

Specified cover = 25 mm

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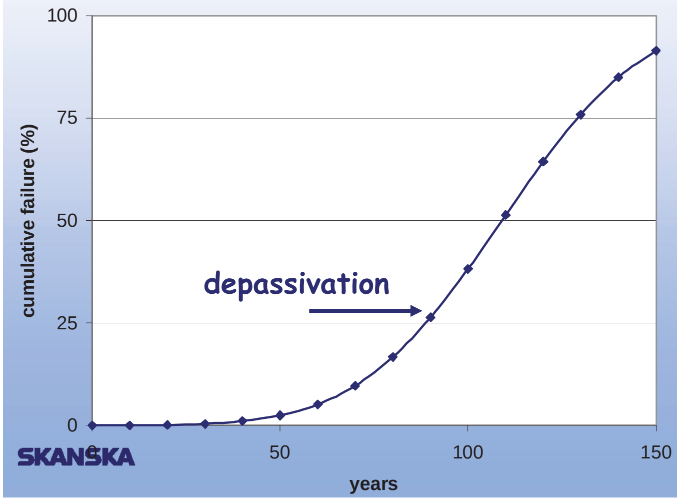
Since all the input parameters to the models have a scatter, the output of the service life design will also have a scatter.



Example:

Depassivation of reinforcement

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Design Service Life - fib & ISO

The design service life is the assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary.

The design service life is defined by:

- *A definition of the relevant limit state*
- *A number of years*
- *A level of reliability for not passing the limit state during this period*

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Limit states

states beyond which the structure no longer fulfils the relevant design criteria

Serviceability limit states (SLS)

states that correspond to conditions beyond which specified service requirements for a structure or structural member are no longer met

Ultimate limit state (ULS)

states associated with collapse or with other similar forms of structural failure

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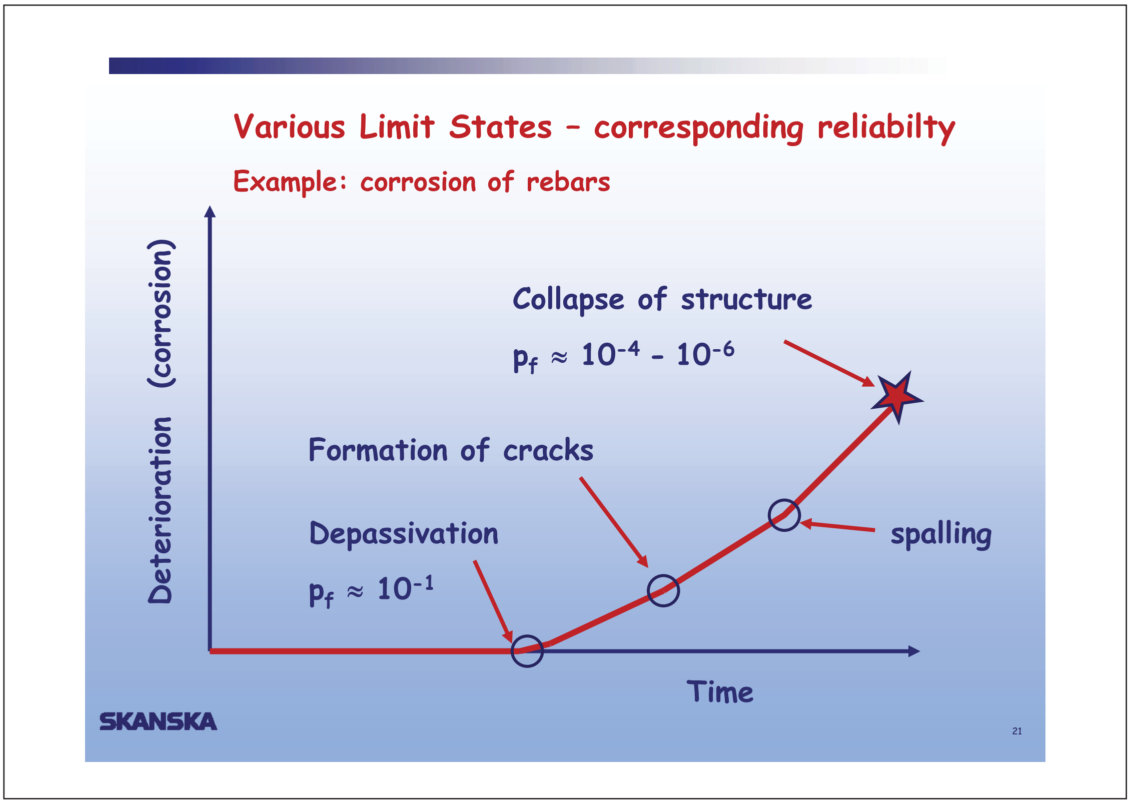
Various Limit States – corresponding reliabilty
Example: corrosion of rebars
Deterioration (corrosion)
Collapse of structure
pf ≈ 10-4 - 10-6
Formation of cracks
Depassivation
pf ≈ 10-1
spalling
Time
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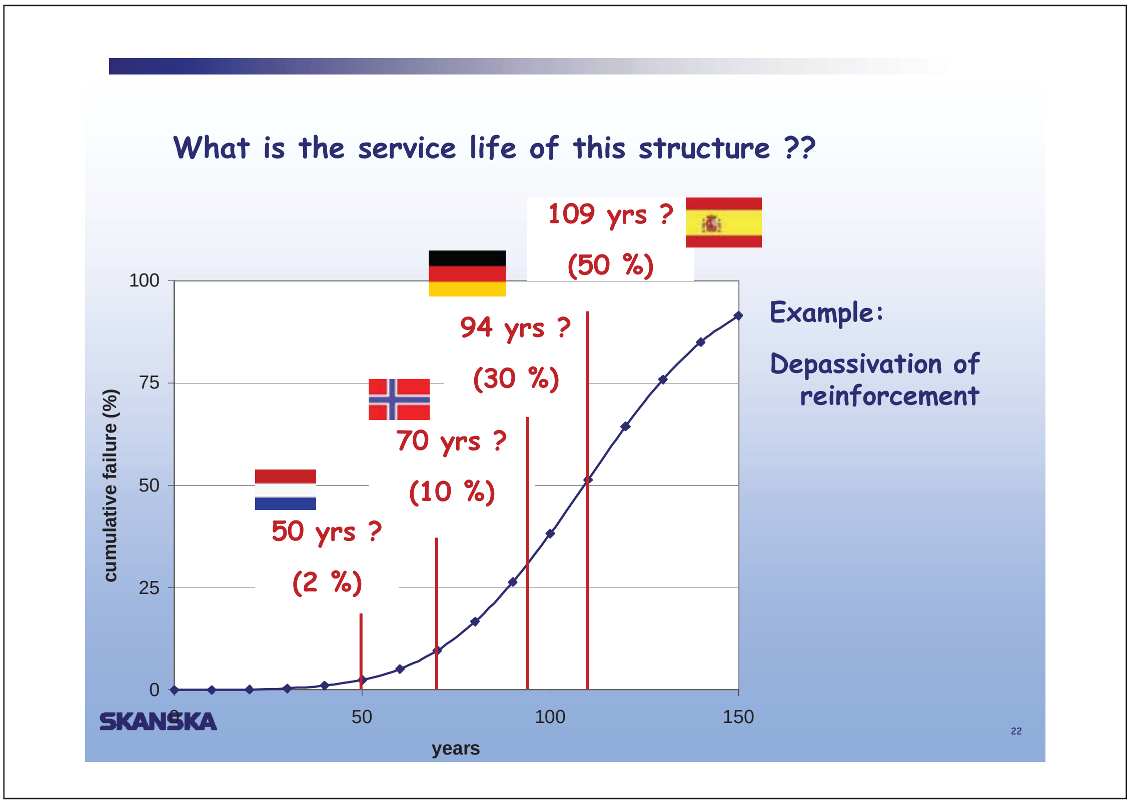
What is the service life of this structure ??
109 yrs ?
(50 %)
94 yrs ?
(30 %)
70 yrs ?
(10 %)
50 yrs ?
(2 %)
Example:
Depassivation of reinforcement
cumulative failure (%)
100
75
50
25
0
0
50
100
150
years
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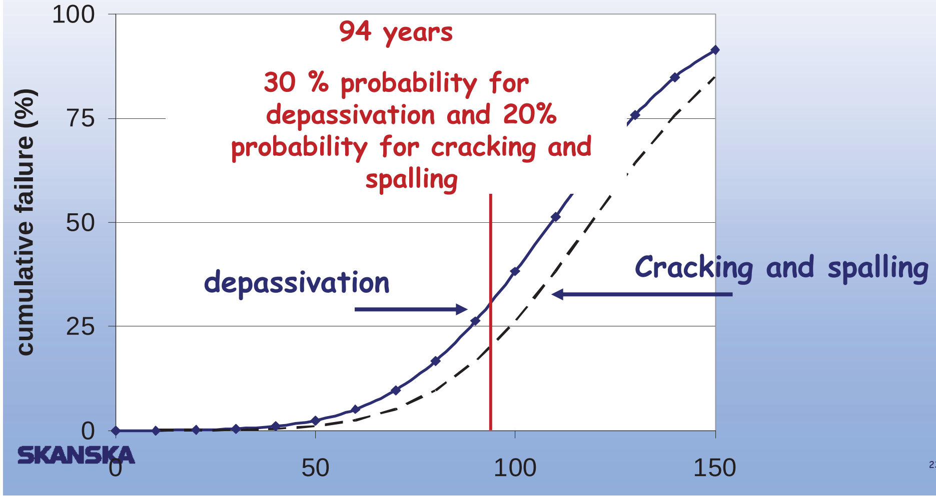
What is the service life of this structure ??



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Direct background for *fib and ISO's* engagement:

Brite Euram "DuraCrete" 1996-1999

Brite Euram "DuraNet" 1998-2001

Tromsø, Norway - Workshop 2001 with participation from Europe and North America

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Probabilistic Service Life design

The main pillars of the concept are:

- to accept that all parameters influencing the deterioration have a statistical spread (both environmetal load and structural resistance).
- The definition of "end of service life" must be quantifiable.
- The concept is therefore Limit State and reliability based.

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International Organization for Standardization ⇨ fib CEB•FIP ⇨ International Organization for Standardization

Resolution ISO/TC 71/N46 –

(9th Plenary Meeting, Oslo 2001-14)

"ISO/TC71 requests that the ISO/TC71 Secretariat inform the fib Secretariat of the intended establishment of ISO/TC71 activity (on Service Life Design – SH Comment) *and expresses strong support for the development of a fib model code on Service Life Design of Concrete Structures"*

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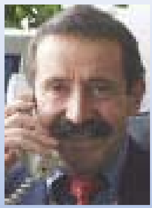
fib Task Group 5.6

"Model Code on Service Life Design of Concrete Structures"



Chairman:
Peter Schiessl

Editorial group:

Schiessl, Helland, Gehlen, Nilsson

Other members:

Rostam, Markeseth, Siemes, Moser, Corley, Bamforth, Markeset, Faber, Ishida, Forbes, Walraven, Helene, Baroghel-Bouny

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Probabilistic Service Life design

- It was a main objective to establish a methodology as close as possible to that applied in structural design
- fib TG 5.6 did therefore chose ISO 2394 "General principles on reliability for structures" as the main reference
- ISO 2390 is the "mother document" for CEN EN 1990)

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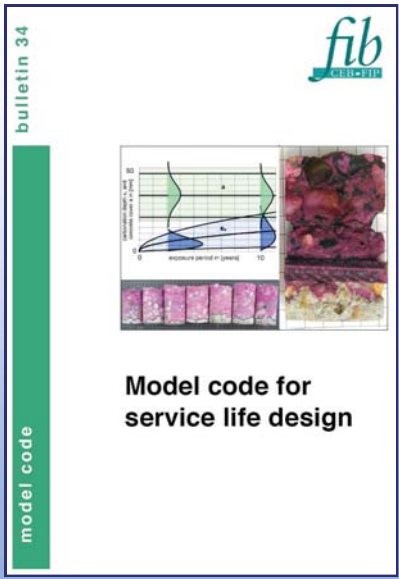

fib MC SLD was approved by the *fib* General Assembly in Naples, June 2006

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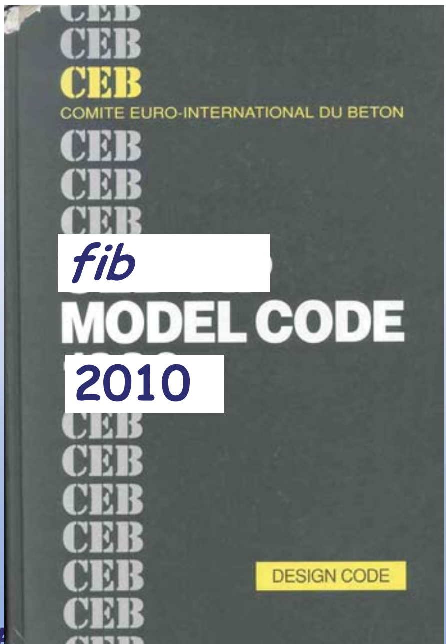

~~*fib* Model Code 1990 is presently under revision~~

fib Model Code 2010 was approved 3 months ago

All the principles of fib MC SLD are implemented

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International Organization for Standardization

ISO TC-71 / SC-3 started their work in 2007 based on the fib document

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ISO TC-71 / SC 3 / WG 4 members:

Steinar Helland, convenor – Norway

Antony Fiorato – US

Zongjin Li – China

Yamei Zhang - China

Lasino – Indonesia

Hari – Indonesia

Siti – Indonesia

Sofia M. C. Diniz - Brazil

Tom Harrison – UK

Koji Sakai – Japan

Philip Bamforth – UK

Marcelo Ferreira – Brazil

Luiz da Silva Filho – Brazil

Mussa Awaleh – UK

Tamon Ueda, SC-7 – Japan

Takafumi Noguchi – Japan

L.da Silva Battagin – Brazil

Manuel Ramirez – Columbia

Viacheslav Falikman – Russia

Carmen Andrade - Spain

Christoph Gehlen – Germany

Peter Schiessl – Germany

Iria Doniak - Brazil

Steinar Leivestad, ex officio – NO

Gregory Zeisler, ex officio – US

Magne Maage, SC 7 – NO (corr)

Yuri Volkov – Russia (corr)

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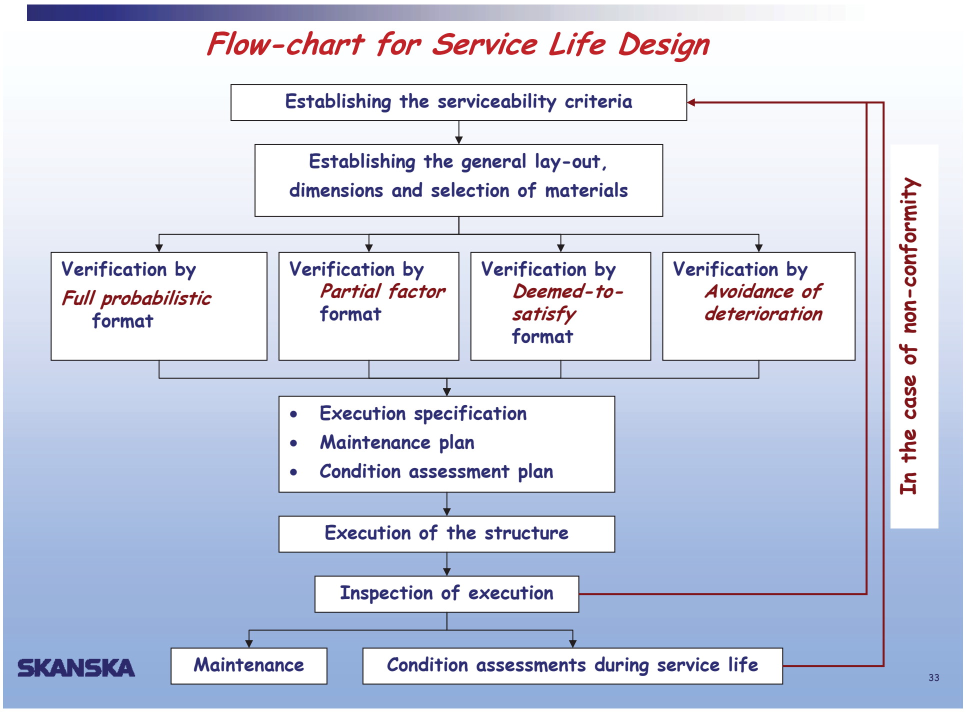

1. "Full probabilistic method". Will seldom be possible for new structures due to lack of statistical data. Will be well applicable for assessments of existing structures

2. "Partial factor method". Based on design values for loads, capacities and geometrical characteristics.

3. "Deemed-to-satisfy" method: Applying tabulated numbers for w/c-ratio, rebar cover, crack width etc. <u>Calibrated according to 1) and/or long-term experience</u>

4. "Avoidance of deterioration". Avoid saturation, apply stainless steel, non-reactive aggregates etc

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Verification by full probabilistic format (Carbonation):

The following requirement shall be fulfilled:

$p\{\} = p_{dep.} = p\{a - x_c(t_{SL}) < 0\} < p_0$

where

$p\{\}$:probability that depassivation occurs

a : concrete cover [mm]

$x_c(t_{SL})$: carbonation depth at the time t_{SL} [mm]

t_{SL} : design service life [years]

p_0 : target failure probability

The variables a and $x_c(t_{SL})$ need to be quantified in a full probabilistic approach.

NOTE: The limit state “depassivation” is only relevant for structures with sufficient humidity to support a corrosion process.

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Verification by full probabilistic format (Carbonation)

Design model:

$$x_c(t) = W \cdot k \cdot \sqrt{t}$$

$x_c(t)$: carbonation depth at the time t [mm]

W : Influence of climate (rain, humidity etc)

k : factor reflecting basic resistance under ref. conditions

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Verification by full probabilistic format (marine structures)

The following limit state function shall be fulfilled:

$P\{\ \} = p_{dep.} = p\{C_{Crit.} - C(a, t_{SL}) < 0\} < p_0$

where

$P\{\ \}$:	probability that depassivation occurs
$C_{Crit.}$:	critical chloride content [wt.-%/binder]
$C(a, t_{SL})$:	chloride content at depth a and time t
a:	concrete cover [mm]
t_{SL}:	design service life [years]
P_0:	target failure probability

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Verification by full probabilistic format (marine structures)

The ingress of chlorides in a marine environment may be assumed to obey the following equation:

$$C(x,t) = C_s - (C_s - C_i) \cdot \left[\mathrm{erf}\left(\frac{x}{2 \cdot \sqrt{D_{app}(t) \cdot t}} \right) \right]$$

$$D_{app}(t) = D_{app}(t_0)\left(\frac{t_0}{t}\right)^{\alpha}$$

Fick's 2nd law of diffuision with a time dependent diffusion coefficient

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Verification by partial factor format (carbonation)

The following limit state function need to be fulfilled:

$a_d - x_{c,d}(t_{SL}) \geq 0$

where

design value of the concrete cover - design value of the carbonation depth ≥ 0

The design value of the concrete cover ad is calculated as follows:

$a_d = a_{nom} - \Delta a$ where a_{nom}: nominal value for the concrete cover

Δa: safety margin (permitted deviation) of the concrete cover

The design value of the carbonation depth, at a time t_{SL}, $x_{c,d}(t_{SL})$ is calculated as follows:

$x_{c,d}(t_{SL}) = x_{c,k}(t_{SL}) \cdot \gamma_f$

where

$x_{c,k}(t_{SL})$: characteristic value of the carbonation depth at a time t_{SL} [mm], e.g. mean value of the carbonation depth

γ_f: partial safety factor of the carbonation depth [-]

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Verification by deemed-to-satisfy format

….is a set of pre-accepted rules for

- Dimensioning
- Material and product selection
- Execution procedures

Normally elements like:

- Cement type
- Max w/c
- Cover thickness
- Crack width limitation

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Verification by deemed-to-satisfy format

….is a set of pre-accepted rules………

Pre-accepted by a responsible standardisation body on behalf of society, public and building owner

The provisions must be calibrated/verified by

- by the full-probabilistic method and/or
- on the basis of long-term experience

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Verification by avoidance of deterioration format

…..implies that the deterioration will not take place due to:

- Separation of environmental load from structure (membranes etc)
- Using non-reacting materials (stainless steel etc)
- Separation of reactants (keeping below a certain degree of moisture etc)
- Supressing the reaction (electrochemical methods etc)

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Other deterioration mechanisms dealt with:

- Freeze-thaw
- Chemical attack
  - Acid
  - Sulphates
  - Alkalie-aggregate reactions

No time-dependent deterioration model available with broad international consensus

The full probabilistic format is therefore difficult to apply

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ISO/DIS 16204 was published in August for international inquiry

Inquiry ended on

February 14th

Final voting and publication expected in 2012

DRAFT INTERNATIONAL STANDARD ISO/DIS 16204

ISO/TC 71/SC 3 Secretariat: SN

Voting begins on 2011-09-14 Voting terminates on 2012-02-14

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION • МЕЖДУНАРОДНАЯ ОРГАНИЗАЦИЯ ПО СТАНДАРТИЗАЦИИ • ORGANISATION INTERNATIONALE DE NORMALISATION

Durability — Service life design of concrete structures

Durabilité — Conception de la durée de vie des structures en béton

ICS 91.080.40

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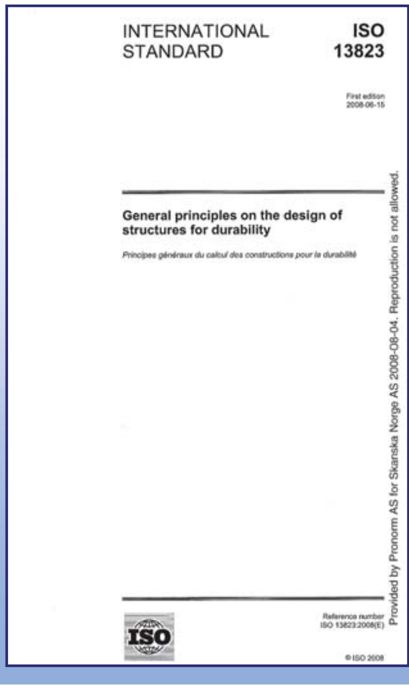
ISO 16204 will also be in line with the principles given by ISO TC-98 in 2008 for service life design of structures in general


INTERNATIONAL STANDARD

ISO 13823

First edition 2008-06-15

General principles on the design of structures for durability

Principes généraux du calcul des constructions pour la durabilité

Reference number ISO 13823:2008(E)

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Scope

This International Standard is intended for the use by national standardization bodies when establishing or validating their requirements for durability of concrete structures.

The standard may also be applied:

- *for assessment of remaining service life of existing structures, and*
- *for the design of service life of new structures provided quantified parameters on levels of reliability and design parameters are given in a national annex to this International Standard*

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Choice of binder in severe exposure classes Swedish experiences and guidelines

Presentation at the Nordic workshop on

Durability aspects of fly ash and slag in concrete

15-16 February 2012 in Oslo, Norway

By Christer Ljungkrantz, Cementa AB

Present Swedish "guidelines"

- **SS 13 70 03:2008 Concrete – Application of EN 206-1 in Sweden**
- **Trafikverket TRV (Swedish Transport Administration):**

- TRVK Bro 11
- AMA Anläggning 10 and TRVAMA Anläggning 10

"Severe exposure classes": XS 3, XD 3 and XF 4.

Choice of binder according to SS 13 70 03:2008 Concrete – application of EN 206-1 in Sweden

Exposure class XS 3, XD 3: (W/C ≤ 0,40)
CEM I, CEM II/A-S, CEM II/A-D, CEM II/A-V, CEM II/A-LL, CEM II/A-M. (Strength class ≥ 42,5)

Exposure class XF 4: (W/C ≤ 0,45)
CEM I, CEM II/A-S, CEM II/A-V, CEM II/A-LL,
CEM II/A-M with max 5 % ”D”. (Strength class ≥ 42,5)

The additions S, D or V may alternatively be added to CEM I in corresponding amount.

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Requirements for concrete binders according to AMA Anläggning 10 and TRVAMA Anläggning 10

The two documents contains requirements for material, and execution of civil engineering structures. For bridges and tunnels the following aply:

Cement shall fulfil the requirements for CEM I in SS-EN 197-1
Cement shall at least fulfil the requirements in
- SS 134202 Moderate heat cement (MH)
- SS 134203 Low alkali cement (LA)
- SS 134204 Sulfate resisting cement (SR)

Fly ash may be added with max 6 % in XF 4 and max 11 % in other exposure classes.

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Present situation

The cement type CEM I 42,5 R MH LA SR has been required by TRV and its predecessors since around 1985, and is accordingly the dominating cement for civil engineering structures in severe exposure classes.

The cement type is manufactured in Sweden under the name ”Anläggningscement”. Last years volume exceeded 400 kton and was produced at both Degerhamn and Slite factory.

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Rationale for use of Anl, durability aspects

Demand for very long service life (120 years) for the TRV-structures

A strong reduction in number of salt frost damages followed the introduction of the cement type.

Temperature cracking susceptibility is low due to moderate heat development and favorable development of strength-, elasticity- and creep-properties in early age.

Sulfate resistance in some ground and tunnel structures.

Low alkali content against slow reacting aggregates and possible interaction with salt frost attack.

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Earlier experiences with blended cements during the 1980:ies

Fly ash cement with about 25 % ash. Also used for bridges.
Production stopped due to problems with air entraining and frost resistance.

Slag cement with about 65 % slag. Mainly for massive structures like power stations.
Production stopped due to cracking and self-healing problems.

CEMENTA HEIDELBERGCEMENT Group

Present use of CEM II cements

CEM II/A-LL is the dominant cement for house building since more than 10 years.

CEM II/A-V and CEM II/B-M (S-LL) are at present under development and testing.

The aim is for house building purpose, but concrete with the cement CEM II/A-V is also tested in severe salt-frost environment at the SP/CBI exposure sites.

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AnI CEM II? Yes but

Assure that the reliable and consistent very good salt frost resistance is not at risk.

- Impact of variable fly ash LOI on dosage of air entrainer and air pore system.
- Deteriorating effect of slag on salt frost scaling in carbonated concrete.

Assure that the enhanced chloride diffusion resistance is not set aside by lower threshold values for start of corrosion

Maintain low temperature cracking susceptibility, sulfate resistance and tolerance against alkali reactive aggregate.

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Replace binder specifications by functional requirements on the concrete?

Functional requirements on concrete for civil engineering structures could enable a more free choice of binders and concrete composition.

This is however a very delicate task, considering the difficulty of establishing criteria, the scatter of test methods and the number of test methods required to assure an solution, as safe as the present well known one, when it comes to all the different perspectives of bridge durability.

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MODELLING THE REACTION OF FLY ASH AND SLAG BLENDED CEMENTS

POST DOC KLAARTJE DE WEERDT, SINTEF/NTNU

1

The ultimate goal

Properties of anhydrous binders

↓

Phase assemblage and porosity

↓

Mechanical properties and durability

2

The ultimate goal

Properties of anhydrous binders

Phase assemblage and porosity

Mechanical properties and durability

3

GEMS

Gibbs free Energy Minimisation Software

- Developed at PSI, Switzerland for Geochemical systems
- Database has been extended for Portland cement system CEMDATA2007 by e.g. B. Lothenbach, T. Matschei, G. Möschner, T. Schmidt

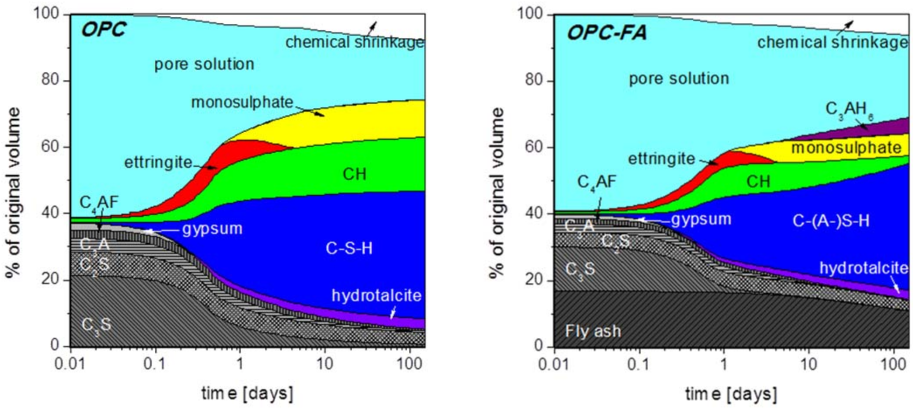
PAUL SCHERRER INSTITUT

EMPA Materials Science & Technology

http://gems.web.psi.ch/
http://www.empa.ch/plugin/template/empa/*/62204/---/l=1

4

Reaction OPC vs. OPC+FA



De Weerdt K, Ben Haha M, Le Saout G, Kjellsen KO, Justnes H, Lothenbach B (2011) Hydration mechanisms of ternary Portland cements containing limestone powder and fly ash. Cement and Concrete Research 41 (3):279-291

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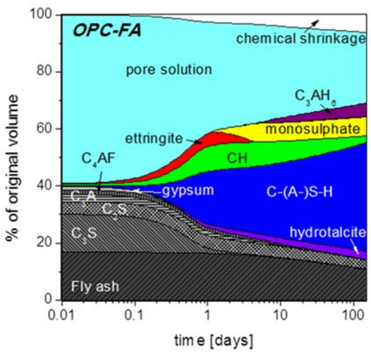
What do we need to know?

1. Reactive content of OPC and fly ash/slag as well as its composition

2. Kinetics of OPC and fly ash/slag reaction

3. The hydrate assemblage



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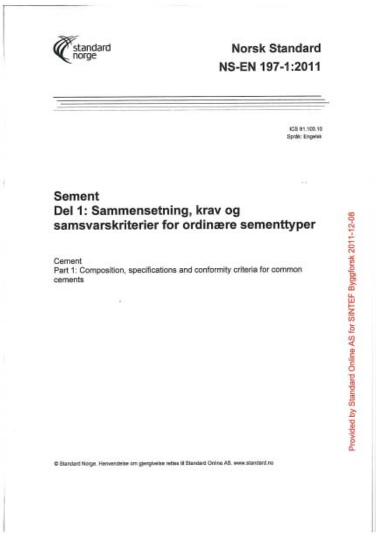
REACTIVE CONTENT AND ITS CHEMICAL COMPOSITION

7

Characterization of FA and slag


standard norge

Norsk Standard
NS-EN 197-1:2011

Sement
Del 1: Sammensetning, krav og samsvarskriterier for ordinære sementtyper

Cement
Part 1: Composition, specifications and conformity criteria for common cements

Provided by Standard Online AS for SINTEF Byggforsk 2011-12-08

Siliceous fly ash (V):
- Reactive CaO < 10%
- Reactive SiO_2 > 25%
- $CaO + Al_2O_3 + SiO_2 > 70\%$

Calcareous fly ash (W)
- Reactive CaO > 10%
- if CaO [10-15%] → reactive SiO_2 > 25%
- if CaO > 15% → compr strength 28 d > 10 MPa

Granulated blast furnace slag (S)
- $SiO_2 + CaO + MgO > 75\%$ mass
- $(CaO + MgO)/ SiO_2 > 1$

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Characterization of FA - norms


Norsk Standard
NS-EN 450-1:2005+A1:2007

Flygeaske for betong
Del 1: Definisjon, spesifikasjoner og samsvarskriterier

Fly ash for concrete
Part 1: Definition, specifications and conformity criteria

Provided by Standard Online AS for SINTEF Byggforsk 2012-01-09

Chemical requirements
- Loss on ignition (<5%, 2%-7%, 4%-9%)
- Chloride content <0.1%
- Sulphuric anhydride < 3%
- Free calcium oxide <2.5%
- Reactive calcium oxide <10%
- Reactive silicon dioxide >25%
- Silicon dioxide, aluminium oxide and iron oxide >70%
- Total content of alkalis <5%
- Magnesium oxide <4%
- Soluble phosphate <0.1‰

Physical requirements
- Fineness >0.045mm <40%, <12%
- Activity index >75%
- Soundness <10mm
- Particle density
- Initial setting time <100% compared to 100% OPC
- Water requirement <95%

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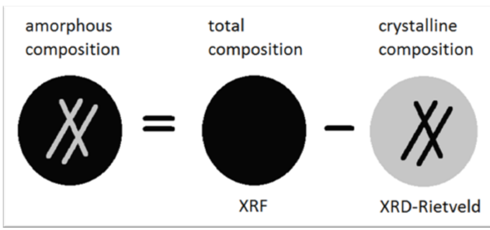
Characterization - research

Chemical characterization
- Composition reactive phase:
  XRF combined with XRD-Rietveld
- Phase composition and distribution:
  SEM-BSE/EDS

Physical characterization
- Fineness:
  laser diffractometry / SEM-BSE
- Particle shape:
  SEM-BSE



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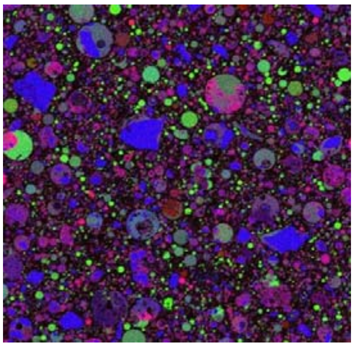
Characterization - research

Chemical characterization

- Composition reactive phase:
  XRF combined with XRD-Rietveld
- Phase composition and distribution:
  SEM-BSE/EDS

Physical characterization

- Fineness:
  laser diffractometry / SEM-BSE
- Particle shape:
  SEM-BSE



Ryan Chancey - https://webspace.utexas.edu/juengerm/lab/hydration.html

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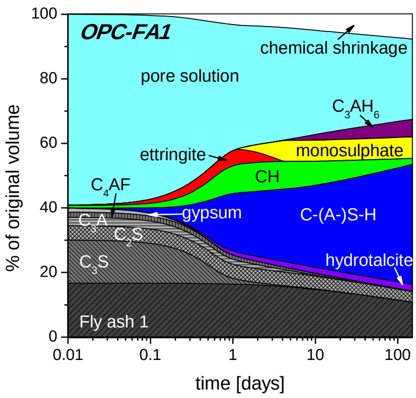
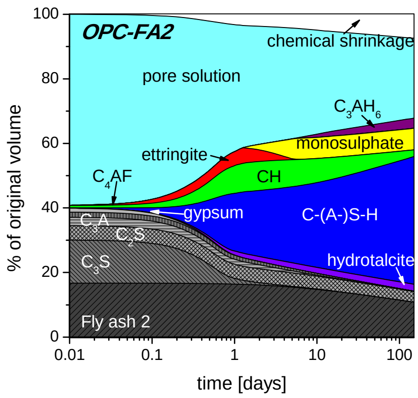
Potential impact of changes is composition



Al_2O_3/SiO_2 = 33%, CaO/SiO_2 = 18%



Al_2O_3/SiO_2 = 14%, CaO/SiO_2 = 16%

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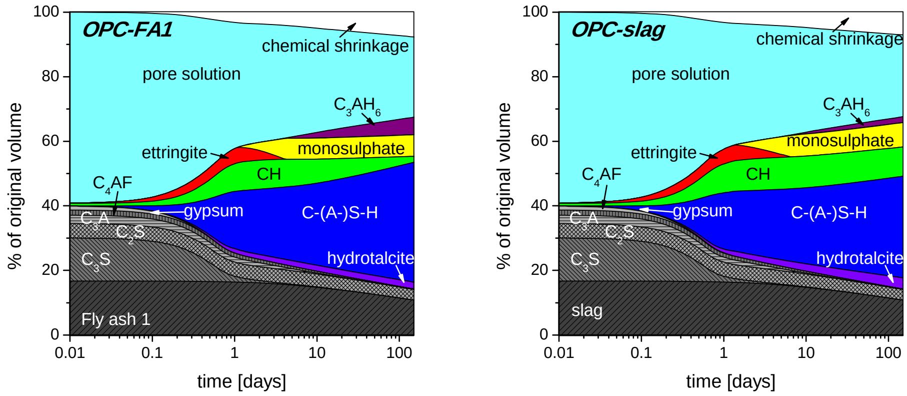
Potential impact of changes is composition



Al_2O_3/SiO_2 = 33%, CaO/SiO_2 = 18%

Al_2O_3/SiO_2 = 34%, CaO/SiO_2 = 118%

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KINETICS OF OPC, FLY ASH AND SLAG REACTION

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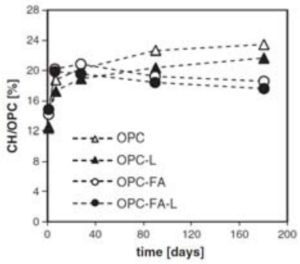
Methods to assess kinetics

Methods	OPC	Blended cements
TGA - amount of bound water	V	/
- CH consumption	/	V (?)
XRD-Rietveld	V	/
SEM (image analysis + EDS)	V	V
^{29}Si NMR (Si phases)	V	V
Selective dissolution	/	/
Isothermal calorimetry	V	V (?)
Chemical shrinkage	V	V (?)



De Weerdt K, Ben Haha M, Le Saout G, Kjellsen KO, Justnes H, Lothenbach B (2011) Hydration mechanisms of ternary Portland cements containing limestone powder and fly ash. Cement and Concrete Research 41 (3):279-291

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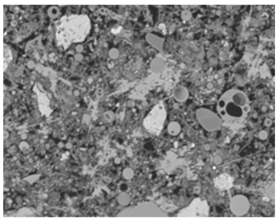
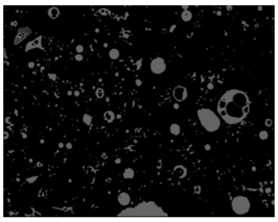
Methods to assess kinetics

Methods	OPC	Blended cements
TGA - amount of bound water	V	/
- CH consumption	/	V (?)
XRD-Rietveld	V	/
SEM (image analysis + EDS)	V	V
^{29}Si NMR (Si phases)	V	V
Selective dissolution	/	/
Isothermal calorimetry	V	V (?)
Chemical shrinkage	V	V (?)





Ben Haha M, De Weerdt K, Lothenbach B (2010) Quantification of the degree of reaction of fly ash. Cement and Concrete Research 40 (11):1620-1629

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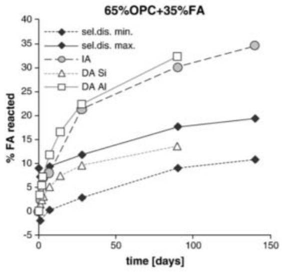
Methods to assess kinetics

Methods	OPC	Blended cements
TGA - amount of bound water	V	/
- CH consumption	/	V (?)
XRD-Rietveld	V	/
SEM (image analysis + EDS)	V	V
^{29}Si NMR (Si phases)	V	V
Selective dissolution	**/**	**/**
Isothermal calorimetry	V	V (?)
Chemical shrinkage	V	V (?)

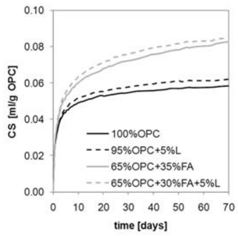


Ben Haha M, De Weerdt K, Lothenbach B (2010) Quantification of the degree of reaction of fly ash. Cement and Concrete Research 40 (11):1620-1629

17

Methods to assess kinetics

Methods	OPC	Blended cements
TGA - amount of bound water	V	/
- CH consumption	/	V (?)
XRD-Rietveld	V	/
SEM (image analysis + EDS)	V	V
^{29}Si NMR (Si phases)	V	V
Selective dissolution	/	/
Isothermal calorimetry	**V**	**V (?)**
Chemical shrinkage	**V**	**V (?)**



What is the "filler effect" and what is caused by the reaction of the SCM?

De Weerdt K, Ben Haha M, Le Saout G, Kjellsen KO, Justnes H, Lothenbach B (2011) Hydration mechanisms of ternary Portland cements containing limestone powder and fly ash. Cement and Concrete Research 41 (3):279-291

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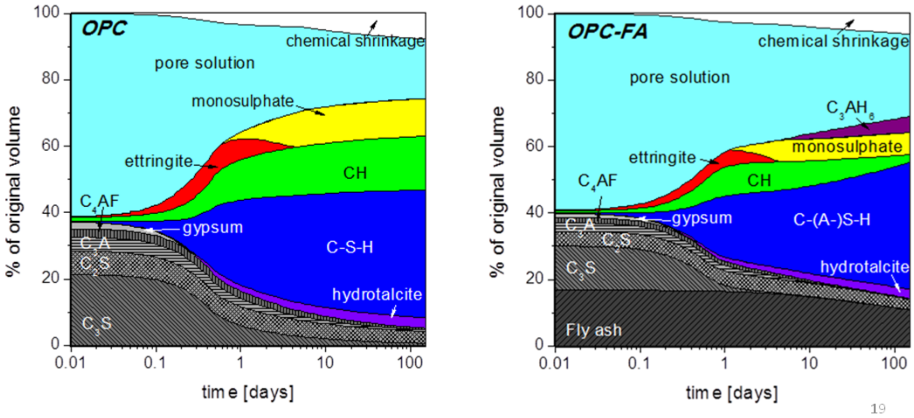
Potential impact of the kinetics

Slow reaction of the SCMs

- reduction in the amount hydration products formed
- slower strength development



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HYDRATE ASSEMBLAGE

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Hydrate assemblage

C-S-H changes upon addition of SCMs

- Ca/Si ratio
- Al uptake – Al/Si ratio
- Na^+, K^+ uptake

Composition changes with

- curing time
- temperature
- replacement level

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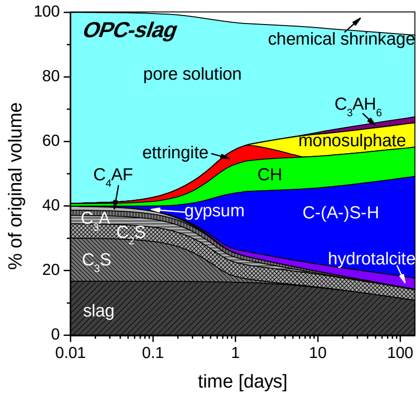
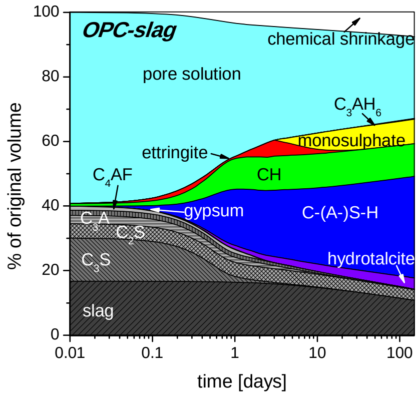
Hydrate assemblage



C-(A)-S-H Al/Si = 0.13



C-(A)-S-H Al/Si = 0.20

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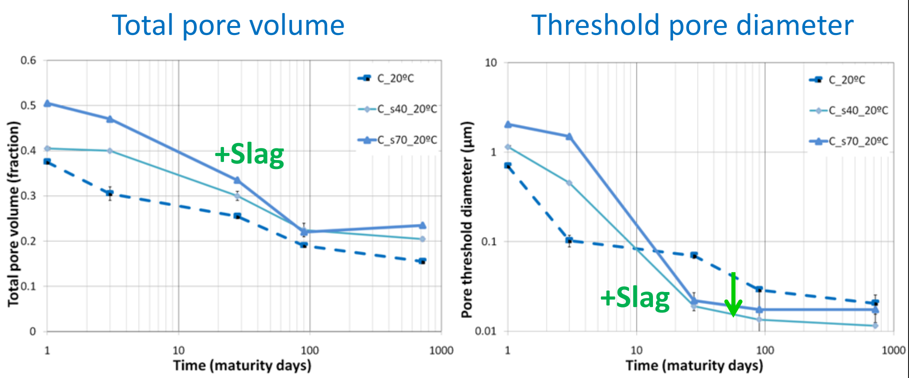
Porosity (MIP)



20ºC, saturated

Canut, M. and M.R. Geiker.
Impact of curing on the porosity development of cement pastes with and without slag.
In proceedings ICCC XIII. 2011. Madrid: p. 260 and CD

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CONCLUSION

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The ultimate goal

Properties of anhydrous binders

Phase assemblage and porosity

Mechanical properties and durability

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The ultimate goal

composition of SCMs

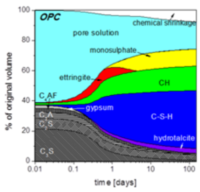
kinetics of reaction

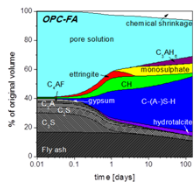
Properties of anhydrous binders

hydration products

Phase assemblage and porosity

Mechanical properties and durability





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Nordic Workshop
Durability aspects of fly ash and slag in concrete
Statens Vegvesen, Oslo 15-16 February 2012

Impact of curing on the porosity and chloride ingress in cement pastes with and without slag

Mette Geiker
NTNU, Dept. of Struc. Eng., NORWAY – and DTU
Mariana Canut and Mads Mønster Jensen
DTU, Dept. of Civ. Eng., Denmark

1

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Motivation

Limited information available on the
impact of curing on the porosity of systems with slag

Needed for

- Mix design and service life design
- Requirements to construction

2

Nordic Workshop, Durability aspects of fly ash and slag in concrete, Oslo, Feb 2012

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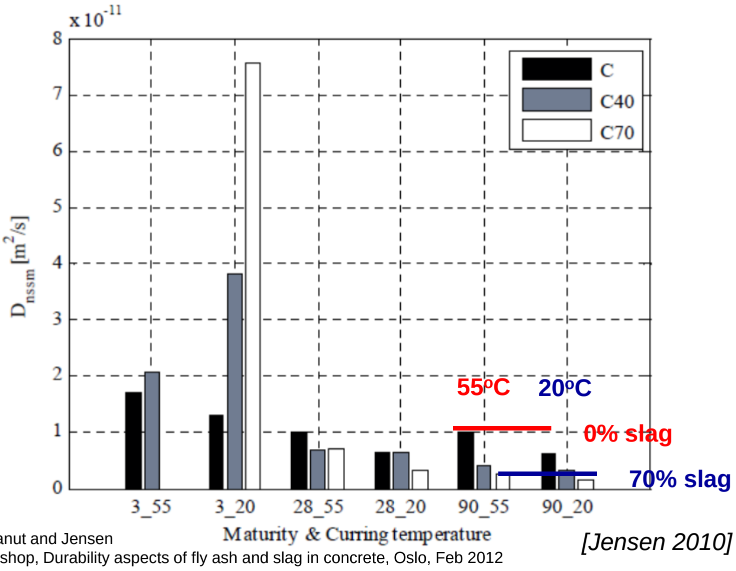
Chloride ingress

(non-steady state chloride migration)



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[Jensen 2010]

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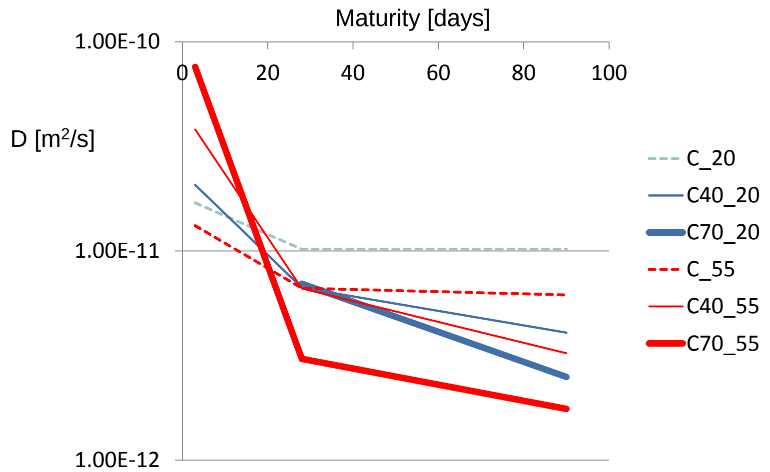
Chloride migration coefficient



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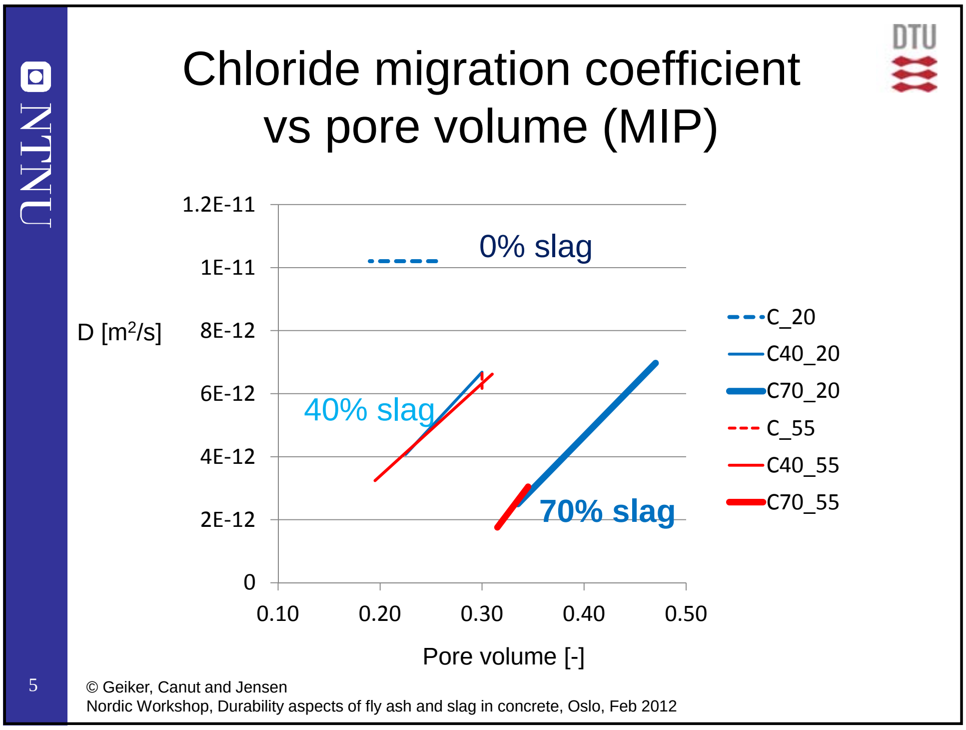
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DTU
Chloride migration coefficient
vs pore volume (MIP)
D [m²/s]
1.2E-11
1E-11
8E-12
6E-12
4E-12
2E-12
0
0.10
0.20
0.30
0.40
0.50
Pore volume [-]
0% slag
40% slag
70% slag
C_20
C40_20
C70_20
C_55
C40_55
C70_55
5
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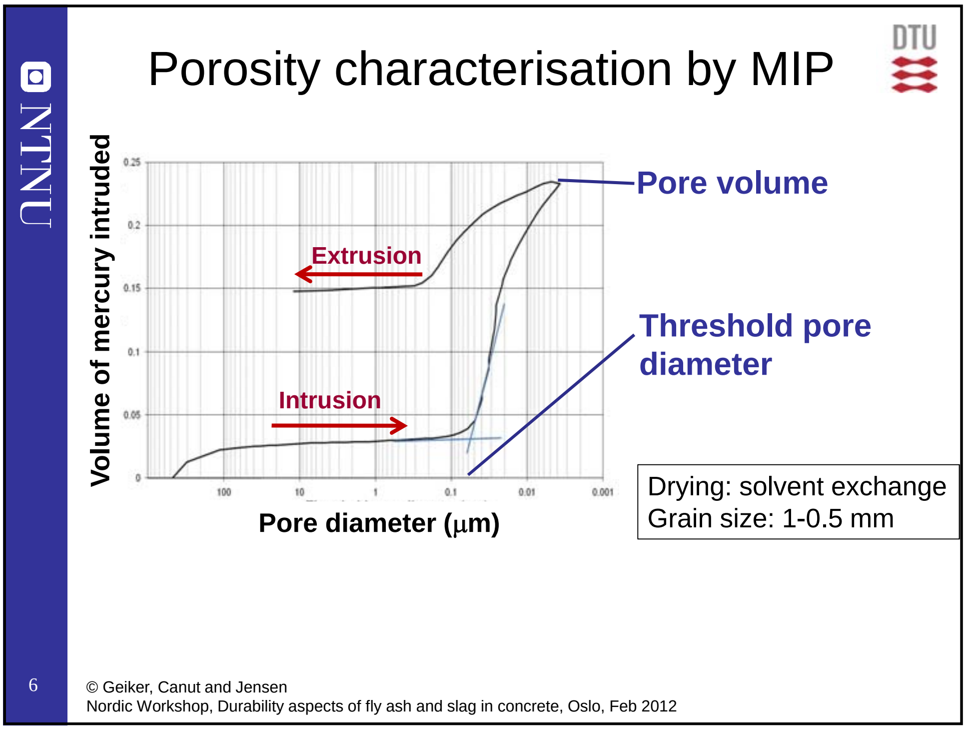
Nordic Workshop, Durability aspects of fly ash and slag in concrete, Oslo, Feb 2012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Porosity characterisation by MIP
Volume of mercury intruded
Pore diameter (μm)
Extrusion
Intrusion
Pore volume
Threshold pore
diameter
Drying: solvent exchange
Grain size: 1-0.5 mm
6
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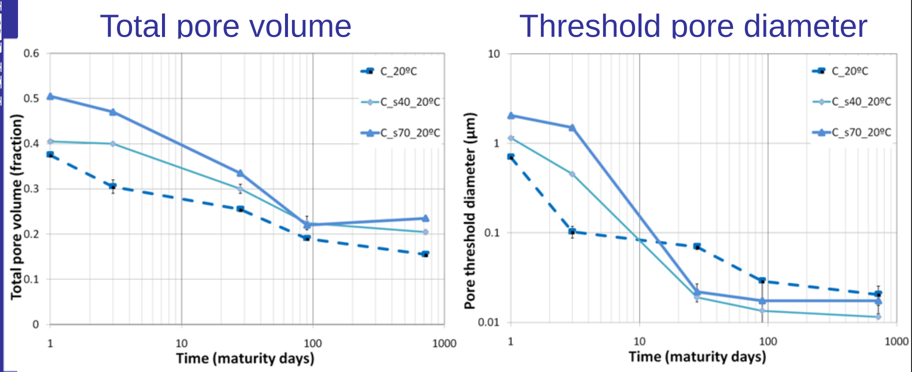
Nordic Workshop, Durability aspects of fly ash and slag in concrete, Oslo, Feb 2012

Impact of slag (20ºC, saturated)



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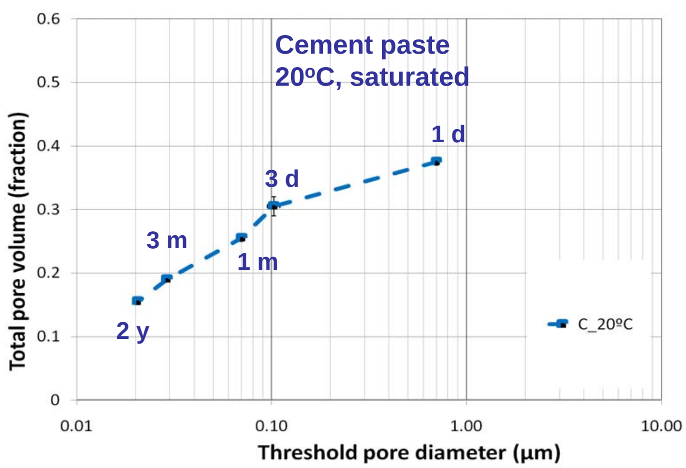
Volume vs. Threshold



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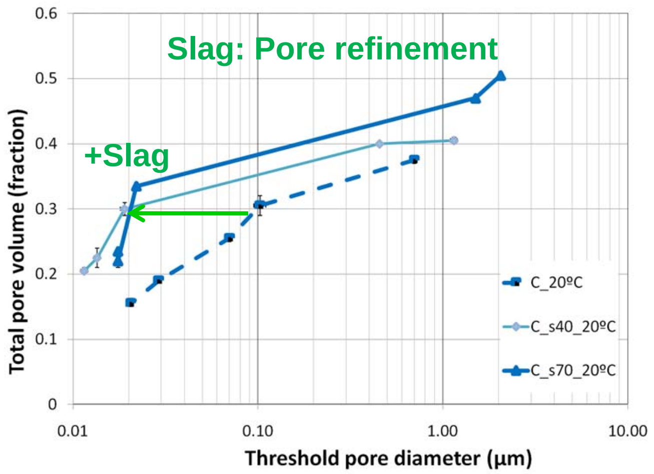
Impact of slag: 20ºC, saturated



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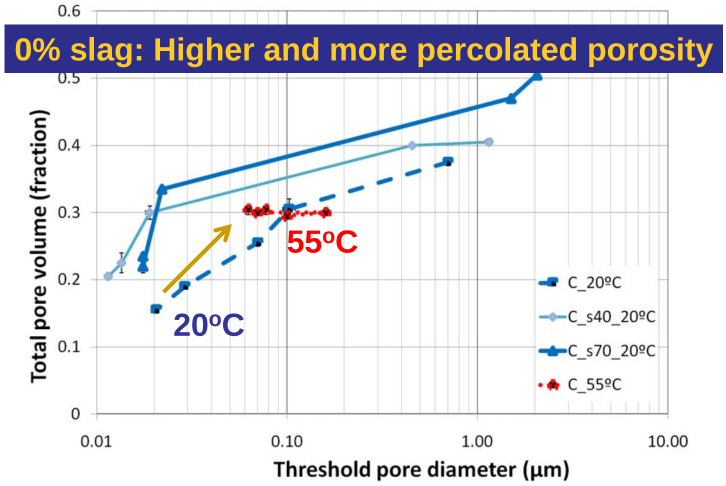
Impact of temperature (saturated)



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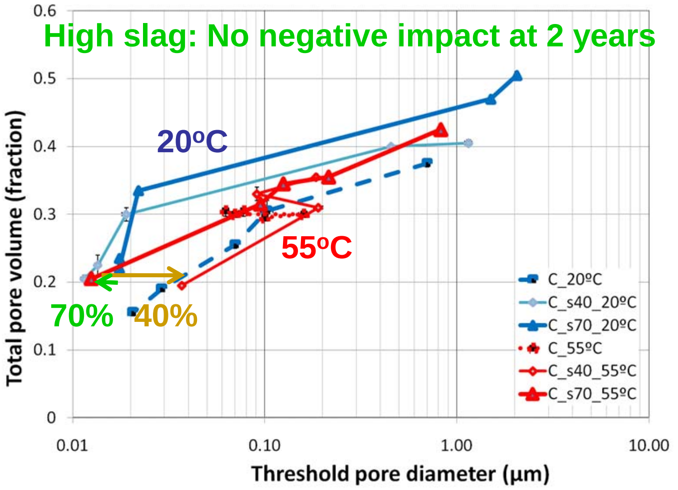
Impact of temperature (saturated)



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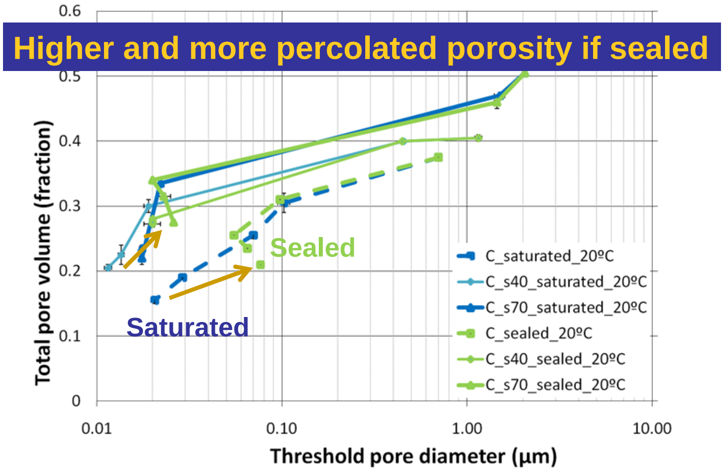
Impact of moisture



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Conclusions and perspectives

Impact of both slag addition and curing on

- **threshold pore sizes and/or pore volume**
- **chloride ingress**

No negative effect of 55°C on 2 years old 70% slag paste

Needed:
Long term studies reflecting realistic conditions

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References

Canut, M. Pore structure in blended cement pastes. PhD thesis, 2011, Department of Civil Engineering, Technical University of Denmark

Canut, M. and M.R. Geiker. Impact of curing on the porosity development of cement pastes with and without slag. *in proceedings ICCC XIII. 2011. Madrid*: p. 260 and CD

Jensen, M.M. Optimisation of sample preparation for SEM and investigation of pore system characteristics in cement paste. MSc thesis, Spring 2010, Department of Civil Engineering, Technical University of Denmark

14

Nordic Workshop, Durability aspects of fly ash and slag in concrete, Oslo, Feb 2012

DTU Civil Engineering
Department of Civil Engineering

DANISH TECHNOLOGICAL INSTITUTE

CONCRETE EXPERTCENTRE

Influence of curing temperature on development of compressive strength and resistance to chloride ingress of concrete with different binder systems

Martin Kaasgaard, Claus Pade, Erik Pram Nielsen
Danish Technological Institute

CONCRETE EXPERTCENTRE

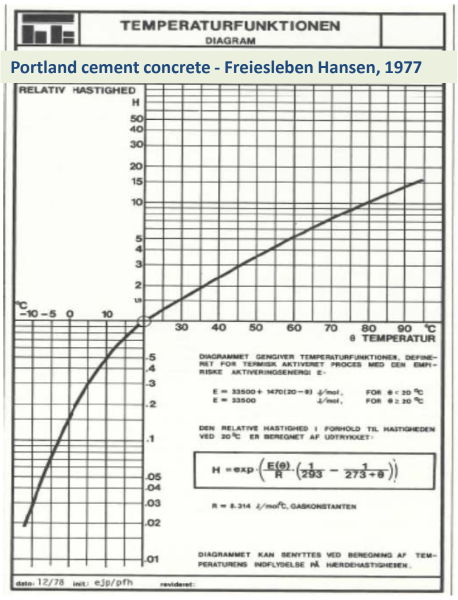
Background

Scope 1

- In Denmark, the maturity concept is used for estimating the strength development of a concrete as a function of temperature – based on data measured at 20 degrees

Input to:

- Optimization of curing
- Striping of formwork
- Evaporation protection
- Selection of binder combination
- Early age crack control

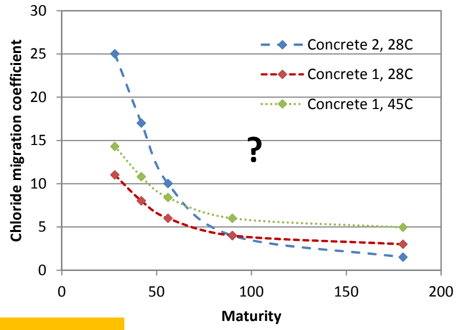


CONCRETE EXPERTCENTRE

Background

Scope 2

Is it possible to use a similar relation to describe the development of resistance to chloride ingress??



Input to:

- selection of binder combination
- optimization of curing
- choice of maturity at first exposure

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Experimental program

Concrete types:

- RPC
- SRPC
- RPC + 25% fly ash
- SRPC + 25% fly ash
- CEM III/B
- SRPC + 4% SF
- SRPC + 4% SF + 12% FA

10°C	20°C	30°C	45°C	60°C
MPa: 1,2,7,28, 56 days	MPa: 1,2,7,28, 56,180 Days	MPa: 1,2,7,28, 56 Days	MPa: 1,2,7,28, 56 days	MPa: 1,2,7,28, 56 Days
NTB492: 28,56,90 ,180 days	NTB492: 28,56,90 ,180 days	NTB492: 28,56,90 ,180 days	NTB492: 28,56,90 ,180 days	NTB492: 28,56,90 ,180 days
NTB443: 28, 180 days	NTB443: 28, 180 days	NTB443: 28, 180 days	NTB443: 28, 180 days	NTB443: 28, 180 days

Slump 120-180 mm

ΔAir content < 0,5% between batches

EN 480-11/batch

NTB388/ batch

Each concrete type: eq. w/c-ratio at 0.40, dmax = 22 mm

78 Ø150 cylinders
30 Ø100 cylinders
500 liter

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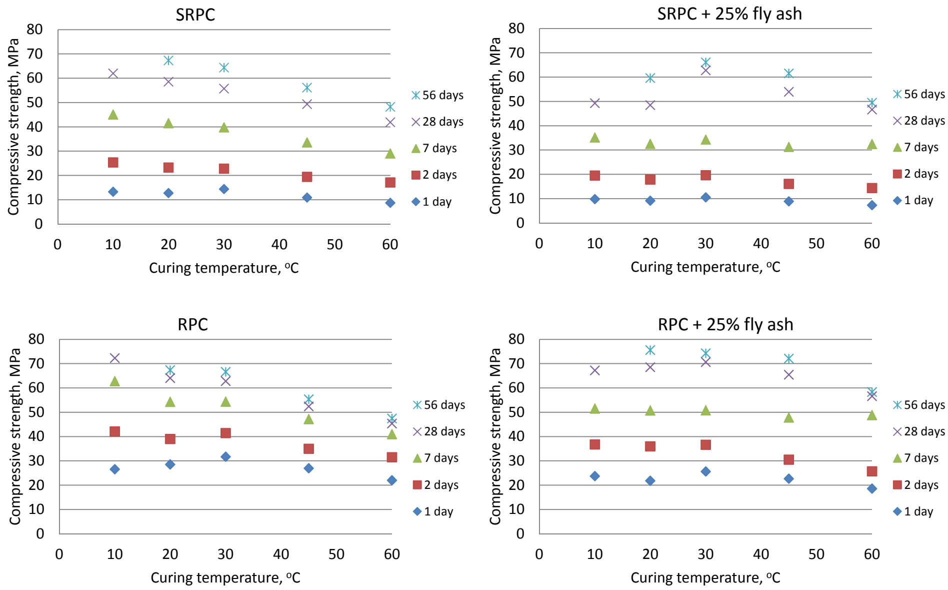
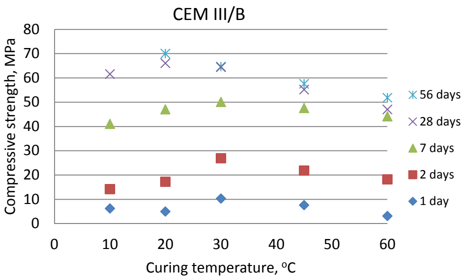
Strength development (in Maturity-days)



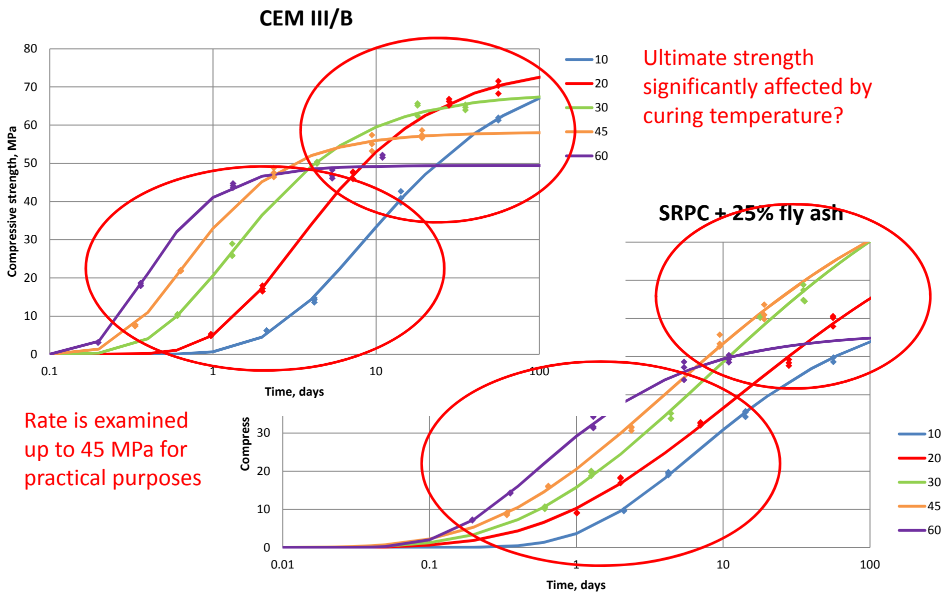
CONCRETE EXPERTCENTRE

Strength development (in Maturity-days)

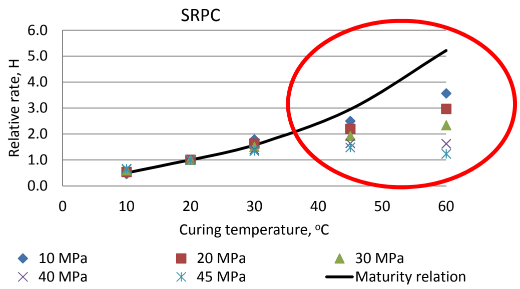


CONCRETE EXPERTCENTRE

Strength development



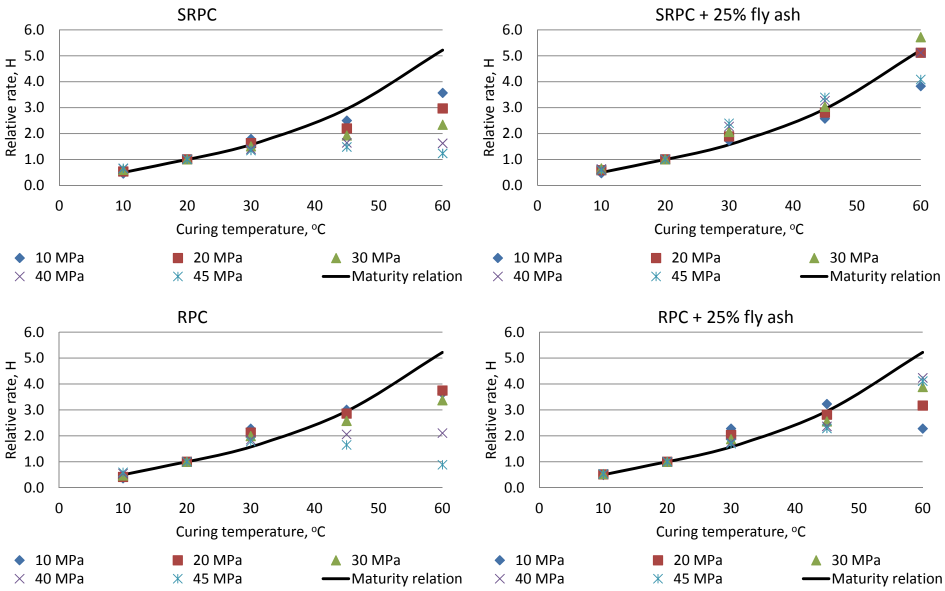
Relative rate of strength development



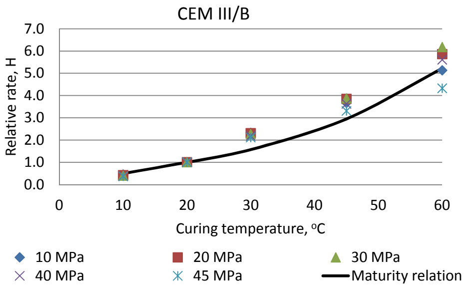
At high temperatures, the rate of strength development is devendent on the degree of hydration!

The energy of activation may be a function of temperature!

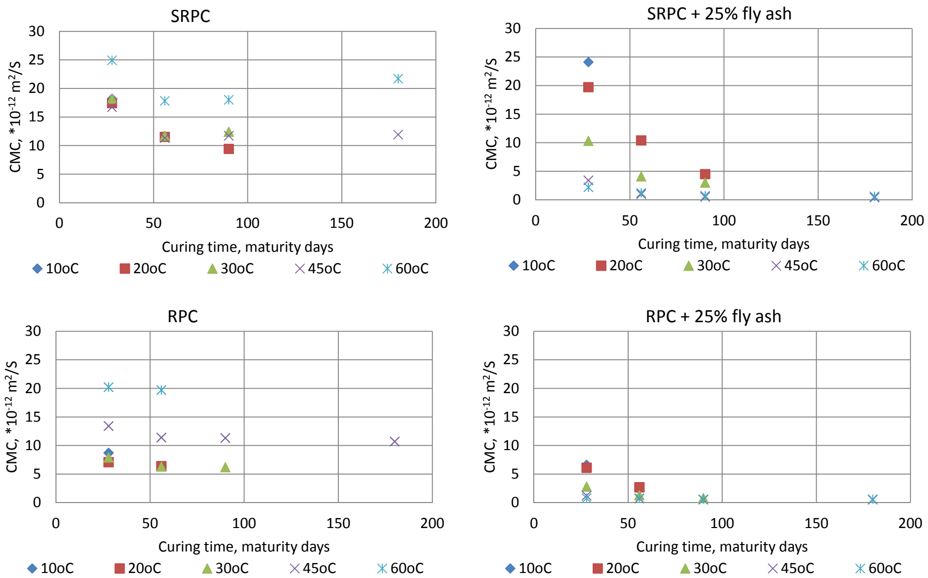
Relative rate of strength development



Relative rate of strength development

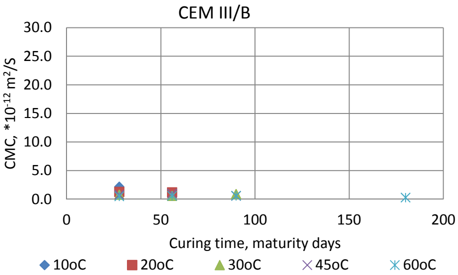


Resistance to chloride ingress (CTH vs. maturity days)



CONCRETE EXPERTCENTRE

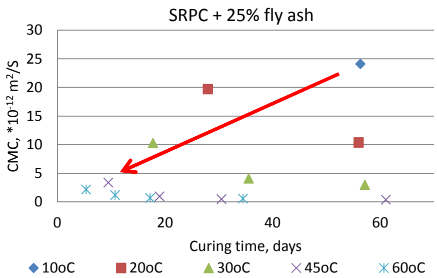
Resistance to chloride ingress (CTH vs. maturity days)

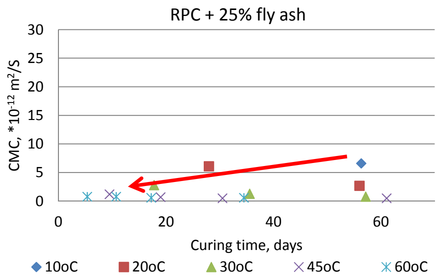


CONCRETE EXPERTCENTRE

Resistance to chloride ingress

- Practical implications – curing strategy





CONCRETE EXPERTCENTRE

Concluding remarks

- The maturity relation by Freiesleben provides an accurate description of the rate of strength development for curing temperatures up to ~30 ^{o}C
- The accuracy of this relation drops significantly for curing temperatures above 30^{o}C, where the rate becomes highly affected by the degree of hydration
- The ultimate strength of a concrete is remarkably affected at curing temperatures around 60 ^{o}C
- Performance of fly ash concretes is greatly improved by high-temperature initial curing
- Slagcement concretes show very good resistance to chloride ingress at short curing times and at all studied curing temperatures
- All studied concretes show remarkably different behaviour with respect to both strength development and resistance to chloride ingress, and therefore…
  - it is recommended to carry out perfomance testing of a concrete at different temperatures prior to execution, in order to plan an optimum curing strategy

The Effect of SCM on Alkali-Aggregate Reaction in Concrete

Oslo Workshop on Durability, Feb. 15 2012

R. Doug Hooton

UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING

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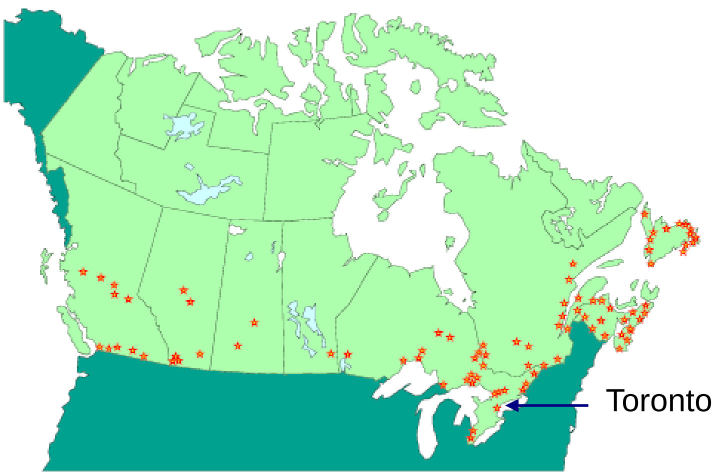
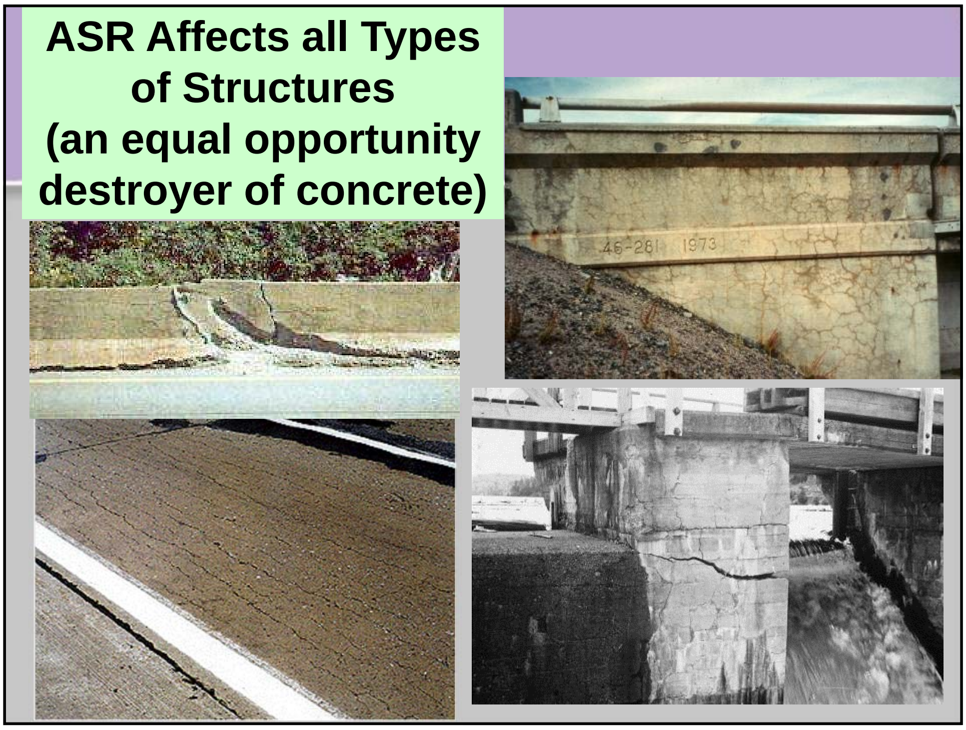
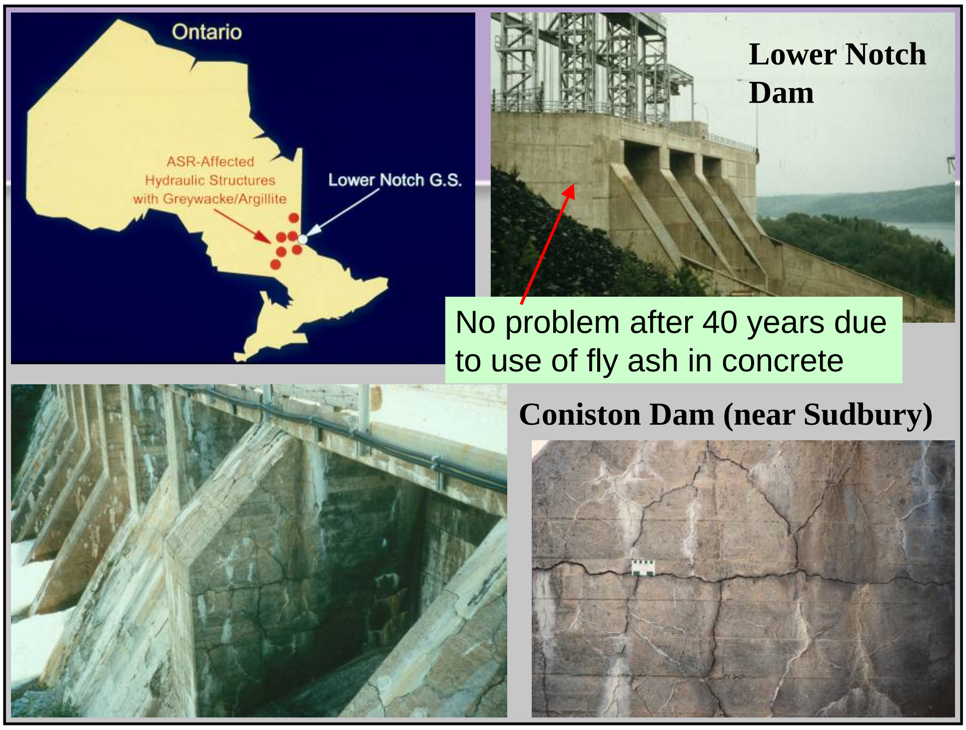
Occurrences of ASR in Canada

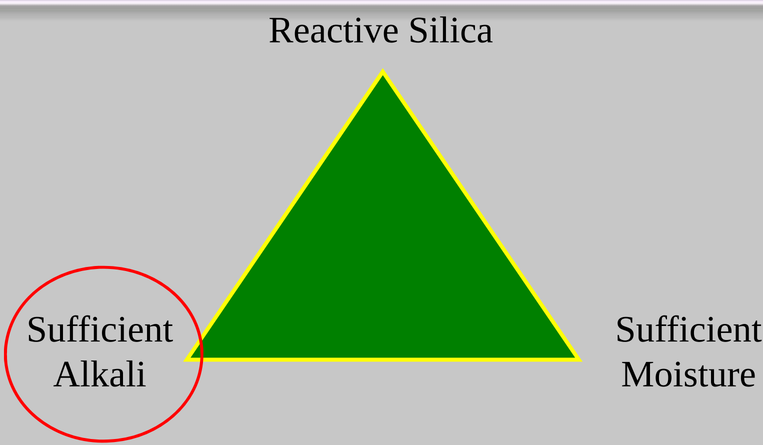


(CSA A864-00)


ASR Affects all Types of Structures
(an equal opportunity destroyer of concrete)
46-281 1973


Ontario
ASR-Affected
Hydraulic Structures
with Greywacke/Argillite
Lower Notch G.S.
Lower Notch
Dam
No problem after 40 years due
to use of fly ash in concrete
Coniston Dam (near Sudbury)

Three Necessities for ASR



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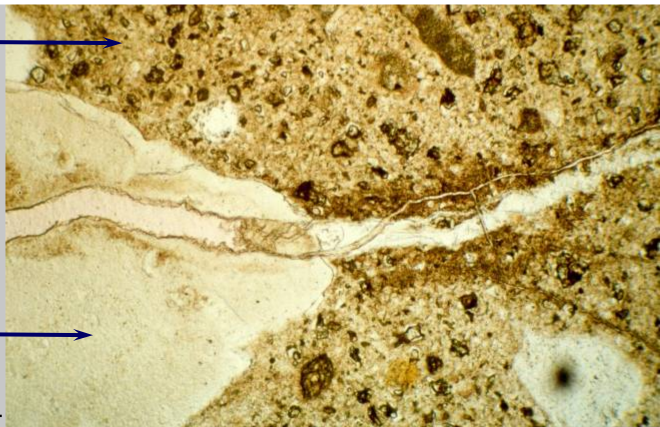
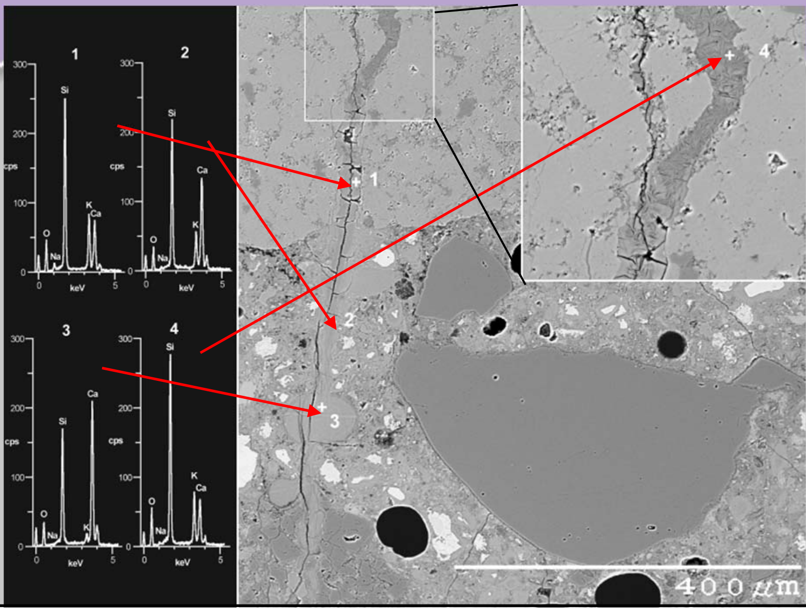
The pore solution of concrete is dominated by alkali (sodium and potassium) hydroxides that originate from the cement. Certain siliceous aggregates may react with the alkali hydroxides to form an alkali-silica gel. This gel has the capacity to imbibe water and swell causing internal pressures that may result in expansion and cracking of the concrete.

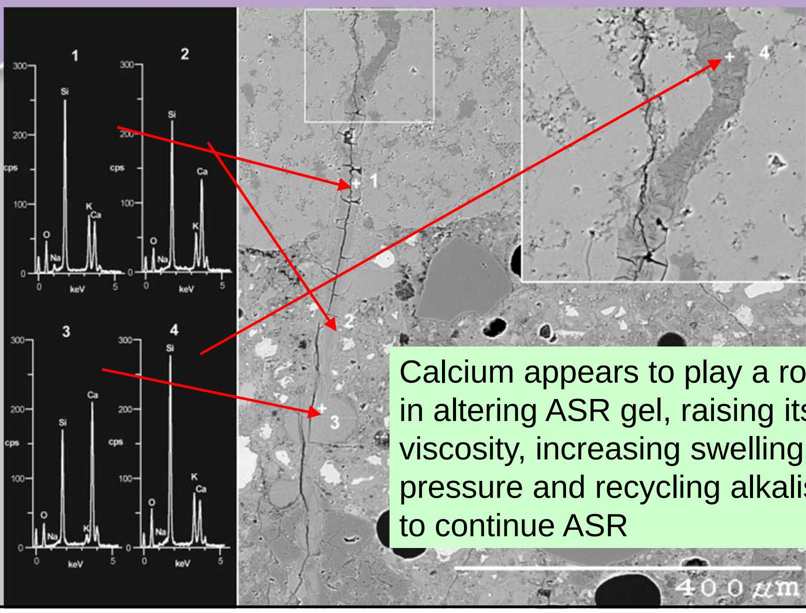


M. Thomas 2011

100% PC Concrete: K/Ca changes as ASR Gel moves from aggregate (1, 4) to paste (2, 3) (Hooton et al 2009)



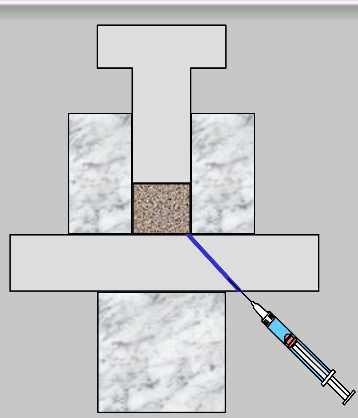
100% PC Concrete: K/Ca changes as ASR Gel moves from aggregate (1, 4) to paste (2, 3)



Calcium appears to play a role in altering ASR gel, raising its viscosity, increasing swelling pressure and recycling alkalis to continue ASR

Pore Solution Analysis

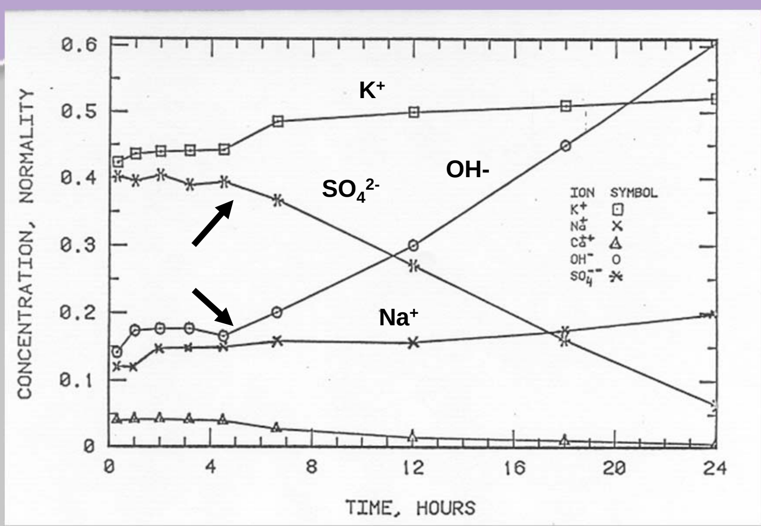
- Cement pastes
- Sealed and cured
- Pore pressed at range of ages
- Solution analysed by titration (OH-)
  & flame photometry (Na & K)



See Barneyback & Diamond 1981

9

Pore solution in 1st 24 hours

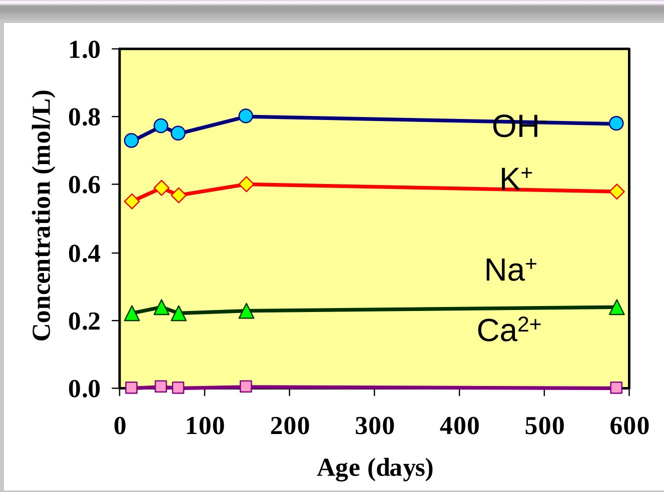


After 24h, mainly K, Na, and OH

S. Diamond

10

Pore Solution alkalinity from 15 to 600 days for portland cement paste

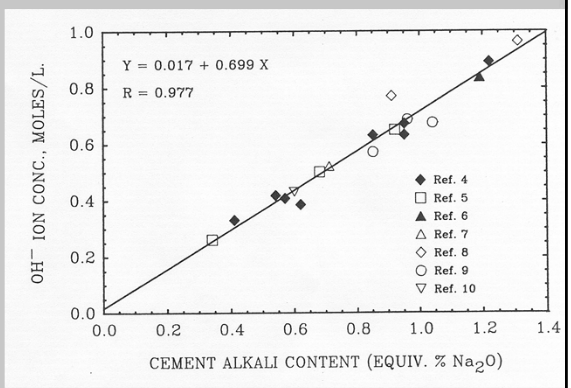


From S. Diamond 1983

11

The “final” OH^- conc. of pore solution is closely linked to cement alkali content

- For a given w:c ratio, the “final” alkali concentration (in sealed systems) is proportional to cement alkali content.
- For a very high alkali cement (Na_2O_{equiv} of 1.4%), the final OH^- ion conc. is ~ 1N, a very concentrated solution used in ASTM C1260!



S. Diamond

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Pore Solution after 24 h (with portland cement)

- Essentially alkali hydroxide solutions: Na^+, K^+, OH^-.
- The solution is also saturated with respect to Ca^{2+}, but its solubility is low in alkali solutions due to common ion effect.
- Unless leaching or moisture movement (or some other ionic ingress) occurs, the alkali hydroxide solution concentrations remain relatively constant over time.

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Pore Solution after 24 h (with portland cement)

- Essentially alkali hydroxide solutions: Na^+, K^+, OH^-.
- The solution is also saturated with respect to Ca^{2+}, but its solubility is low in alkali solutions due to common ion effect.
- Unless leaching or moisture movement (or some other ionic ingress) occurs, the alkali hydroxide solution concentrations remain relatively constant over time (but with SCM's the pore solution alkalinity changes over time as alkalis get taken up in hydrated phases).

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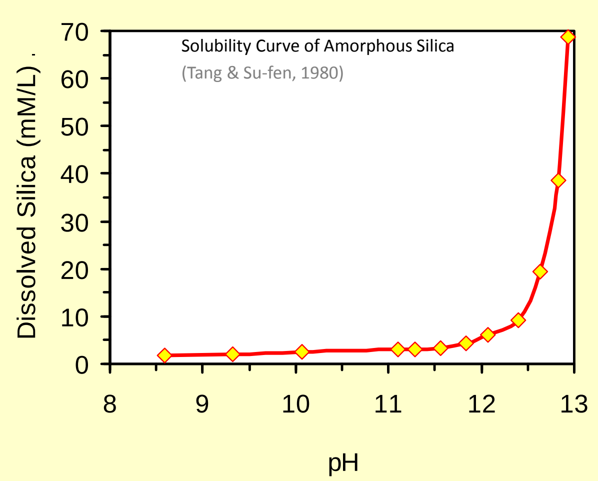
Role of Alkalis

Effect of the pH of the alkali solution on the solubility of amorphous silica →



pH of Concrete is 13-14

Crystalline silica solubility is low at high pH at ambient temperatures

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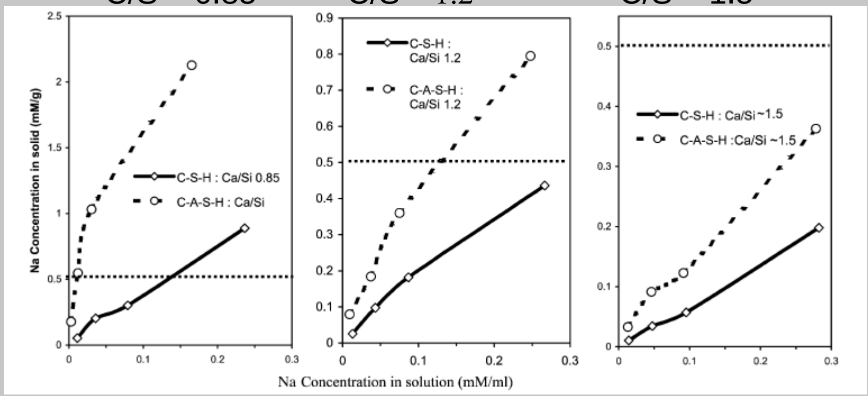
How do SCMs Mitigate ASR?

- The main factor appears to be a reduction in pore solution alkalinity due to incorporation of alkalis into the lower Ca/Si C-S-H which is also increased by presence of Al_2O_3 in SCMs to form low Ca/SI C-A-S-H.

Effect of alumina in C-S-H on alkali binding

S.-U. Hong, F.P. Glasser (2002)

C/S = 0.85 C/S = 1.2 C/S = 1.5



This explains the beneficial effect of fly ash, slag & metakaolin in alkali binding, as well as improvements with low Ca/Si C-S-H

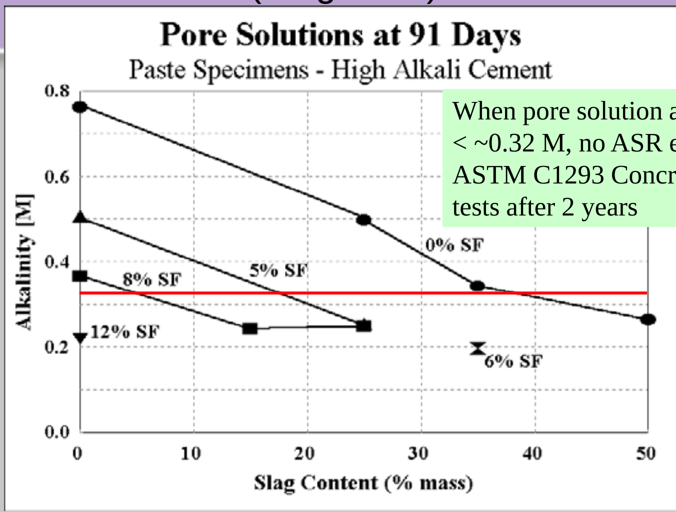
Composition of the C-S-H

- The **Ca/Si** molar ratio of the C-S-H is **lower**; reduced from about 1.9 for Portland cement to as low as ~1.6 for silica fume and Class F fly ash mixes.
  - Partly due to incorporation of '**extra**' **Si** atoms derived from SCMs, but also have **lower Ca**.
- The **Al/Ca** ratio is **higher** when SCM contains high amounts of reactive Al_2O_3, especially metakaolin and fly ash.
  - The Al^{3+} is tetrahedrally coordinated, substituting for silicon.

	Ca/Si	**Al/Ca**
Portland	**1.94**	**0.050**
8% Silica fume	**1.60**	**0.053**
8% Metakaolin	**1.69**	**0.074**
25% Blast-furnace slag	**1.83**	**0.056**
25% Class F ash	**1.57**	**0.095**
25% Class C ash	**1.73**	**0.069**

T. Ramlochan, 2003

Reduction in Pore Solution Alkalinity with SCMs (Slag + SF)



When pore solution alkalinity was < ~0.32 M, no ASR expansion in ASTM C1293 Concrete prism tests after 2 years

(Bleszynski, Hooton & Thomas, 2000)

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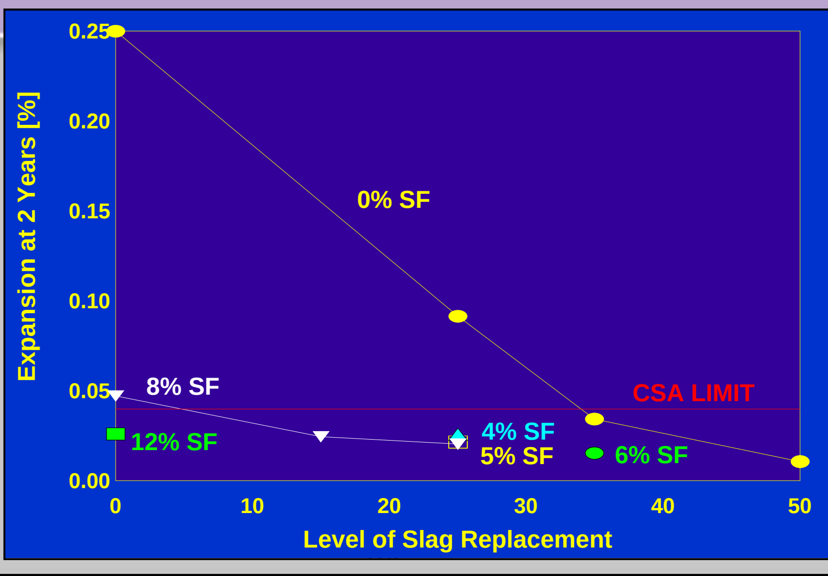
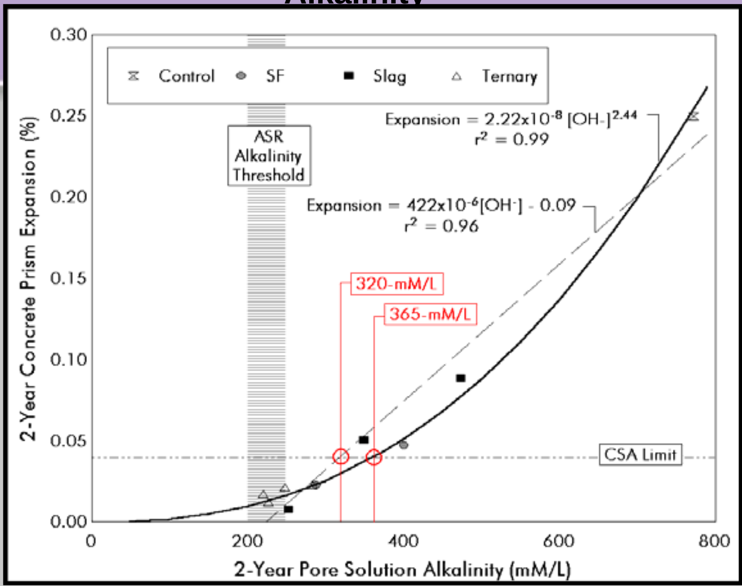
Summary Plot of 2-Year Concrete Prism Expansion with Spratt Aggregate



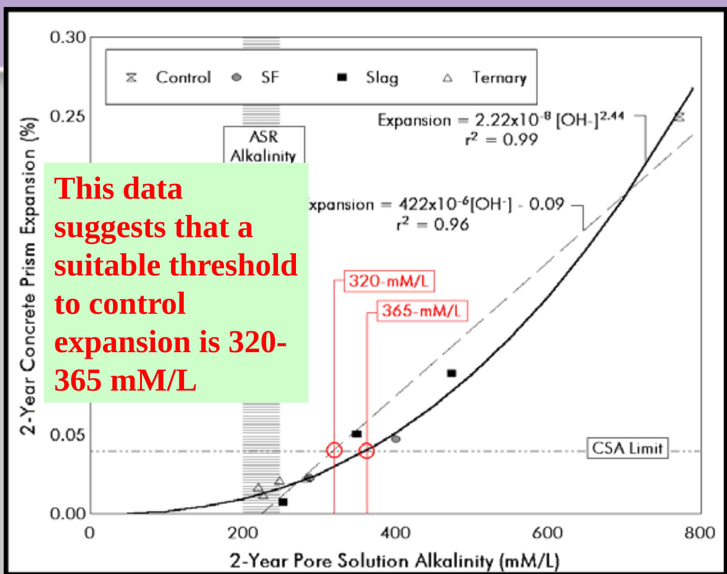
Relationship between Expansion and Pore Solution Alkalinity



1

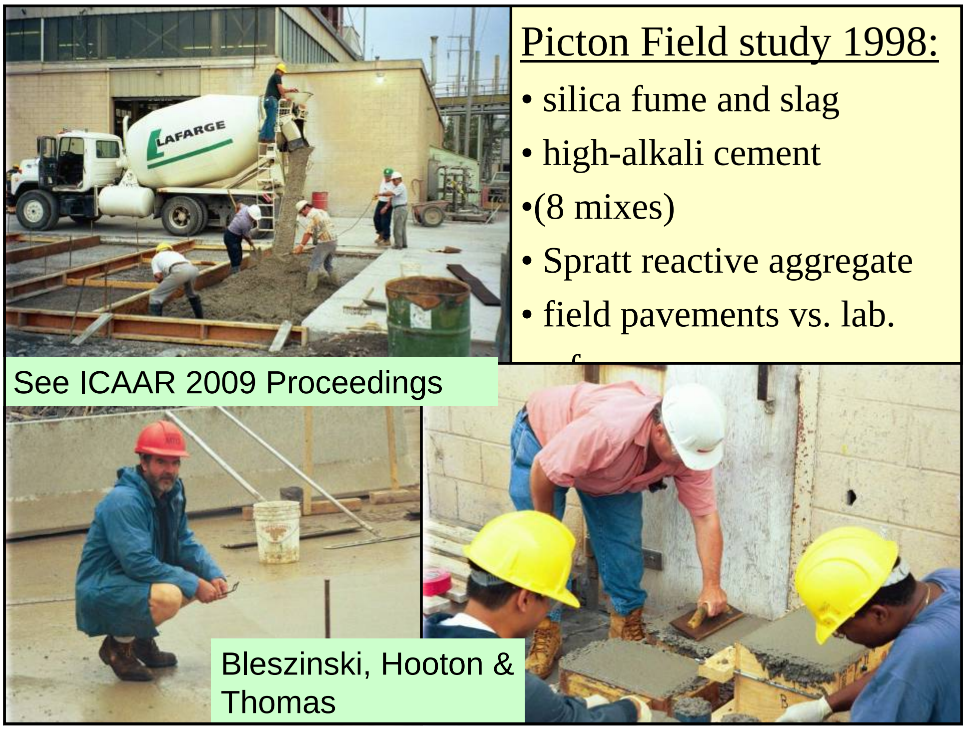
(Bleszynski, Hooton & Thomas)

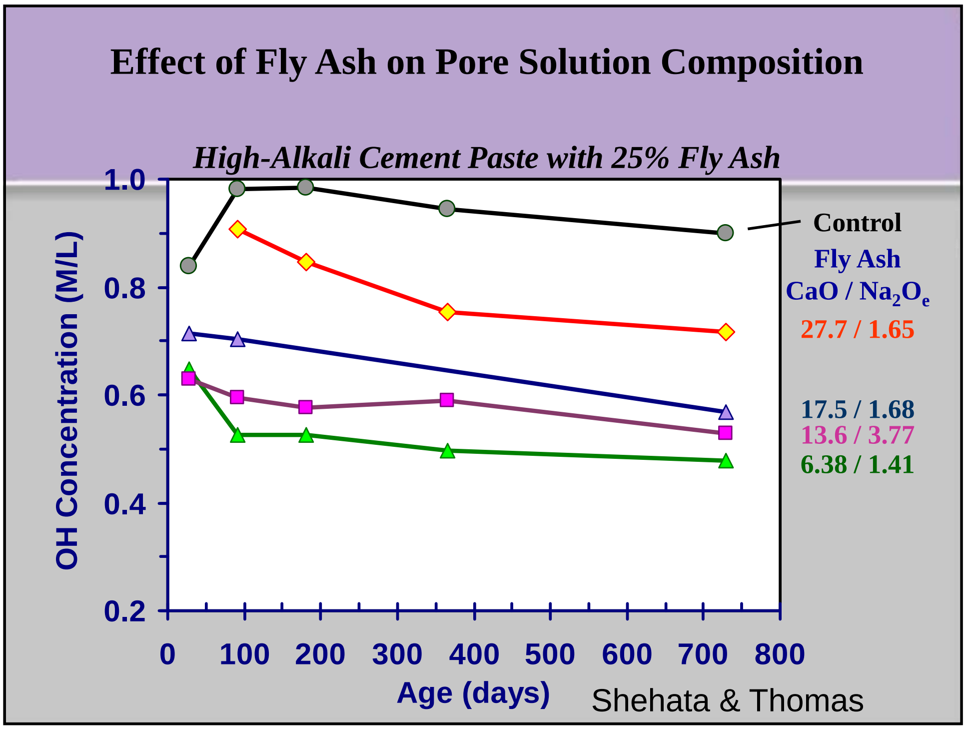
Relationship between Expansion and Pore Solution Alkalinity

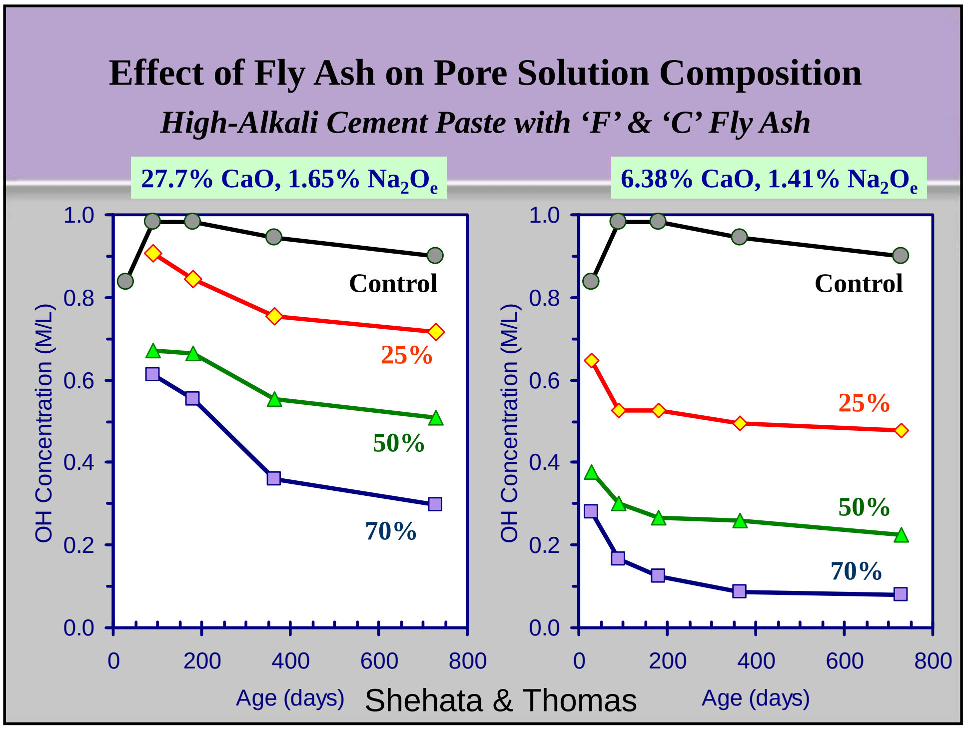


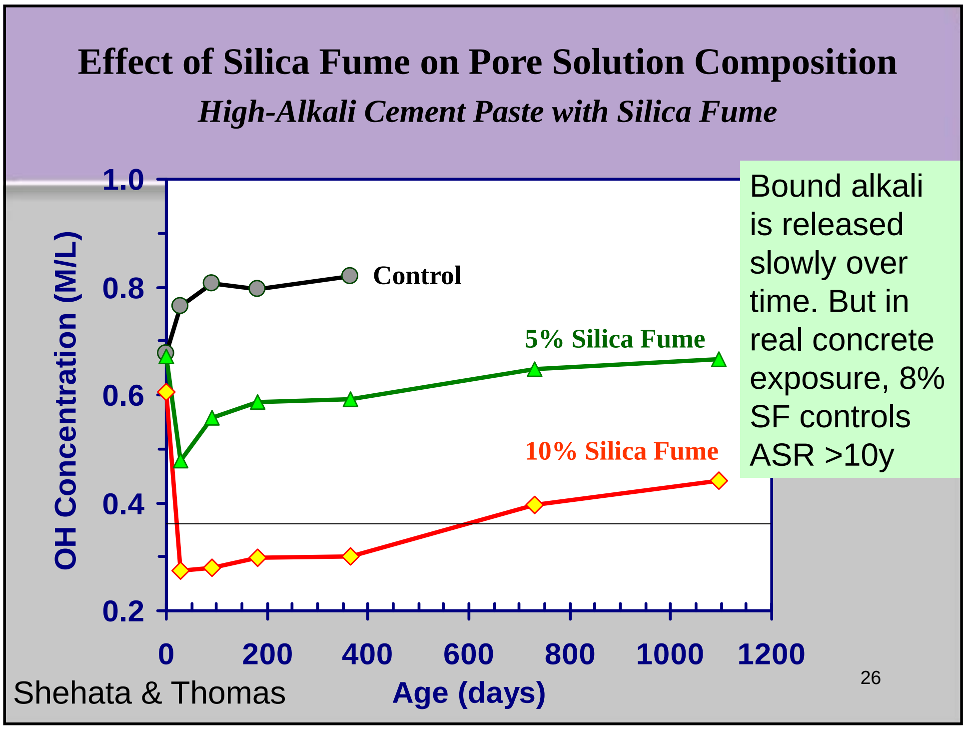
2

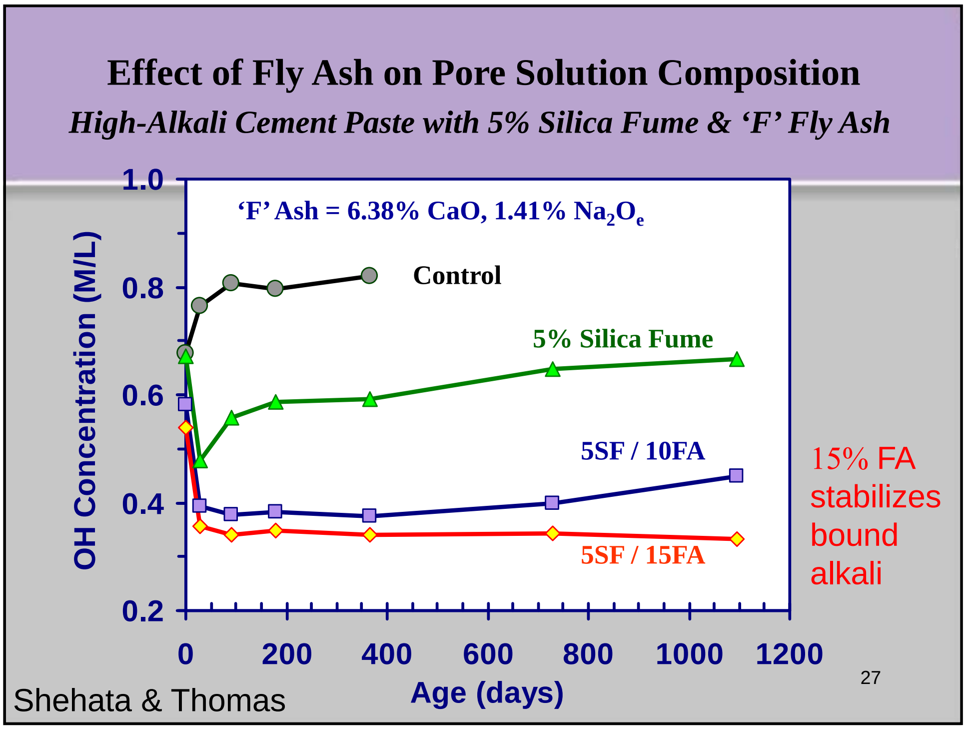
(Bleszynski, Hooton & Thomas)

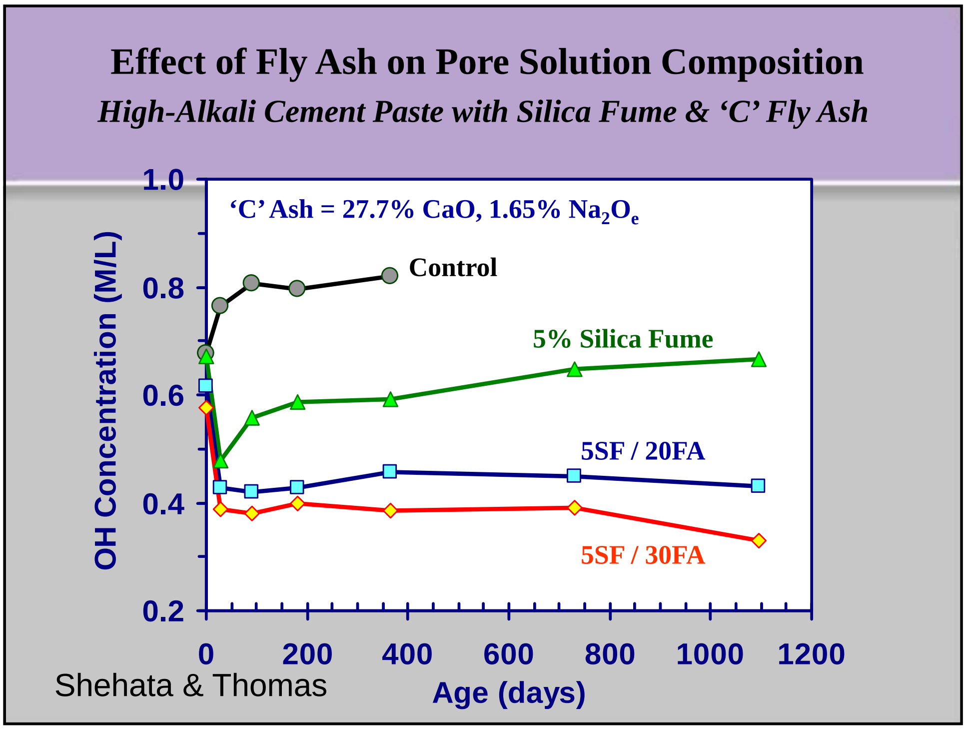

Picton Field study 1998:
• silica fume and slag
• high-alkali cement
•(8 mixes)
• Spratt reactive aggregate
• field pavements vs. lab.
See ICAAR 2009 Proceedings
LAFARGE
Bleszinski, Hooton & Thomas


Effect of Fly Ash on Pore Solution Composition
High-Alkali Cement Paste with 25% Fly Ash
OH Concentration (M/L)
1.0
0.8
0.6
0.4
0.2
0
100
200
300
400
500
600
700
800
Age (days)
Control
Fly Ash
CaO / Na_2O_e
27.7 / 1.65
17.5 / 1.68
13.6 / 3.77
6.38 / 1.41
Shehata & Thomas


Effect of Fly Ash on Pore Solution Composition
High-Alkali Cement Paste with 'F' & 'C' Fly Ash
27.7% CaO, 1.65% Na2Oe
6.38% CaO, 1.41% Na2Oe
OH Concentration (M/L)
Control
25%
50%
70%
Age (days)
Shehata & Thomas

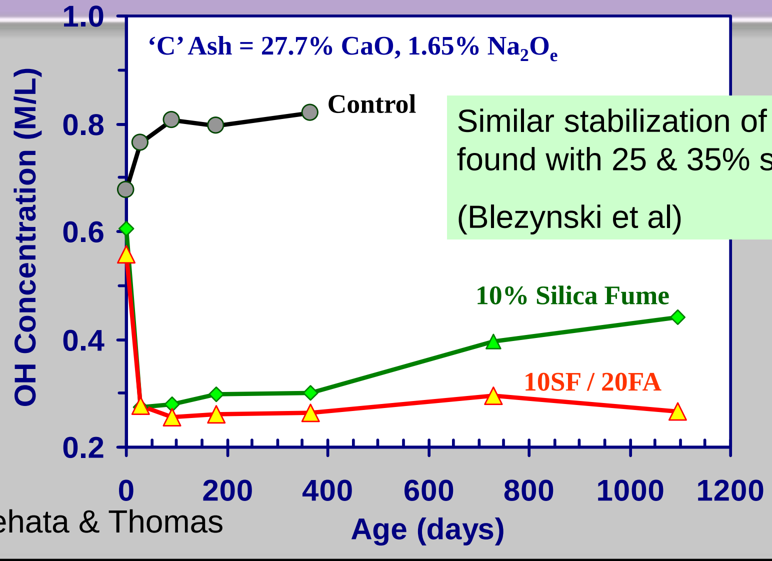

Effect of Silica Fume on Pore Solution Composition
High-Alkali Cement Paste with Silica Fume
Bound alkali is released slowly over time. But in real concrete exposure, 8% SF controls ASR >10y
OH Concentration (M/L)
Control
5% Silica Fume
10% Silica Fume
Age (days)
Shehata & Thomas
26


Effect of Fly Ash on Pore Solution Composition
High-Alkali Cement Paste with 5% Silica Fume & 'F' Fly Ash
'F' Ash = 6.38% CaO, 1.41% Na_2O_e
Control
5% Silica Fume
5SF / 10FA
5SF / 15FA
15% FA stabilizes bound alkali
OH Concentration (M/L)
1.0
0.8
0.6
0.4
0.2
0
200
400
600
800
1000
1200
Age (days)
Shehata & Thomas
27


Effect of Fly Ash on Pore Solution Composition
High-Alkali Cement Paste with Silica Fume & 'C' Fly Ash
'C' Ash = 27.7% CaO, 1.65% Na_2O_e
Control
5% Silica Fume
5SF / 20FA
5SF / 30FA
OH Concentration (M/L)
1.0
0.8
0.6
0.4
0.2
0
200
400
600
800
1000
1200
Age (days)
Shehata & Thomas

Effect of Fly Ash on Pore Solution Composition

High-Alkali Cement Paste with Silica Fume & 'C' Fly Ash



Similar stabilization of [OH-] found with 25 & 35% slag

(Blezynski et al)

Shehata & Thomas

Concrete Prism Test

CSA A23.2-14A ASTM C 1293

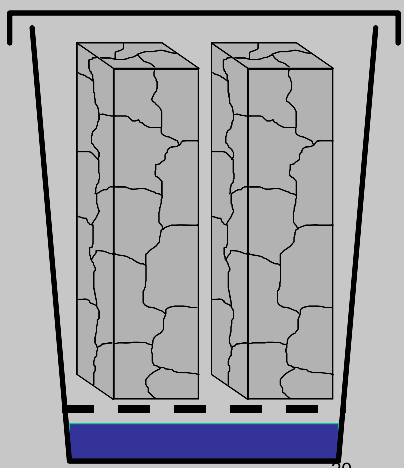
420 kg/m³ cementitious material

NaOH added to yield 1.25% Na_2O_e by mass of Portland cement

0.42 ≤ W/CM ≤ 0.45

Concrete prisms
75 x 75 x 250 mm (min)

Stored over water at 38°C
(and nominally 100% RH)
for 2 years



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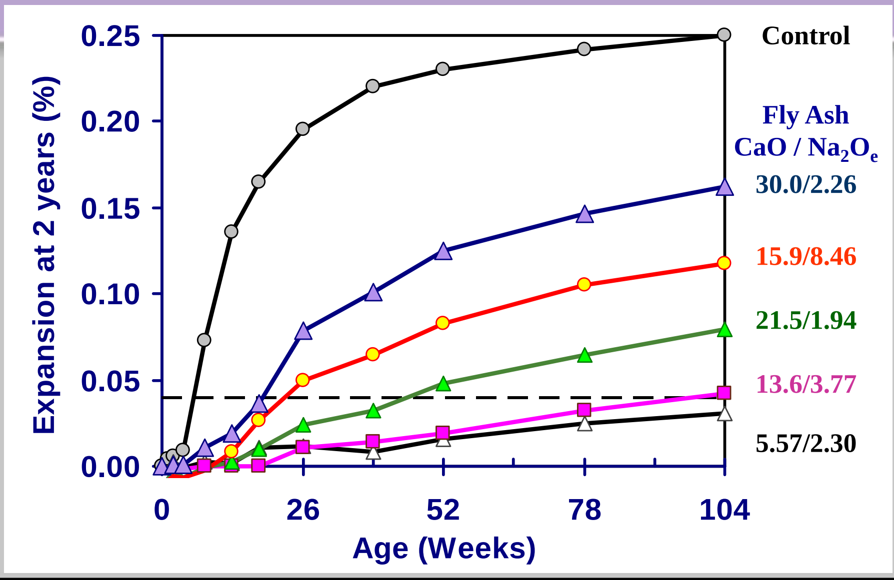
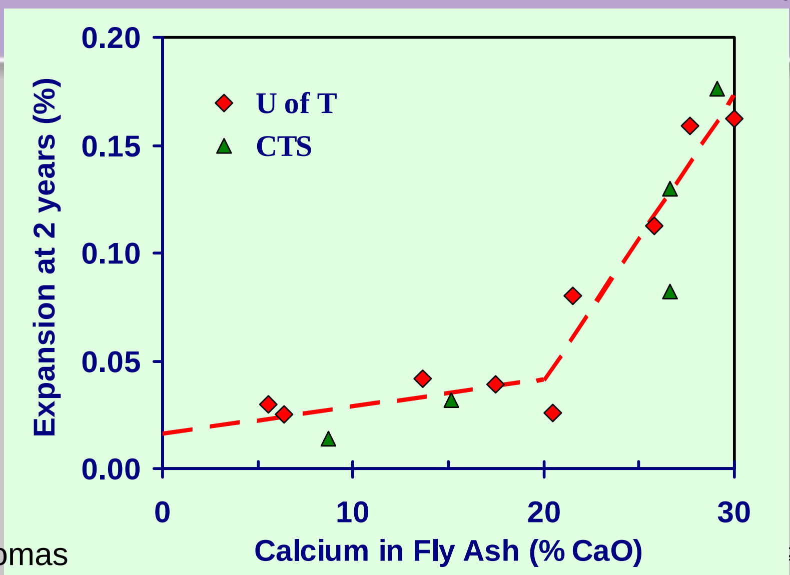
Effect of Fly Ash on ASR Expansion

Concrete Prisms with 25% Fly Ash & Spratt Aggregate



Effect of Calcium Content of Fly Ash on ASR Expansion

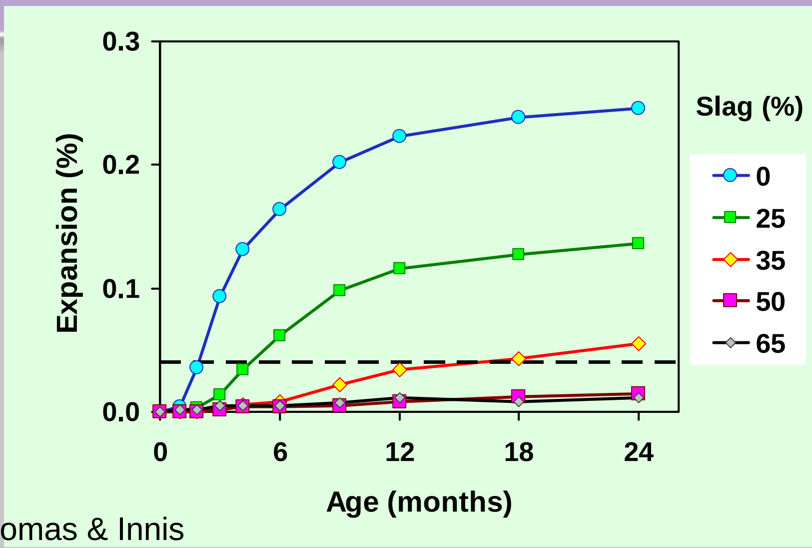
Concrete Prisms with 25% Fly Ash (All ashes < 4.0% Na_2O_e)



Thomas

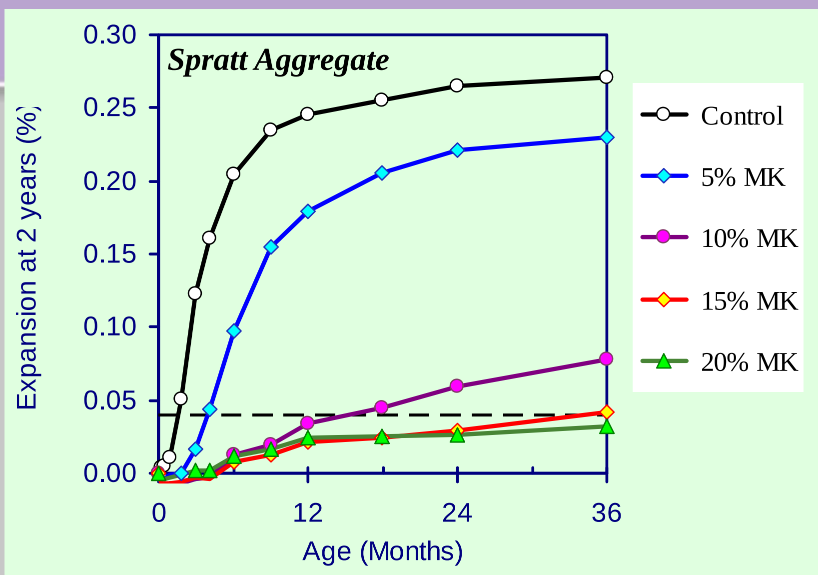
Expansion of Concrete Prisms with Slag

Spratt - 1.25% Na_2O_e (by mass of PC)



Thomas & Innis

Effect of Metakaolin on ASR Expansion



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Ramlochan

Accelerated Mortar Bar Test

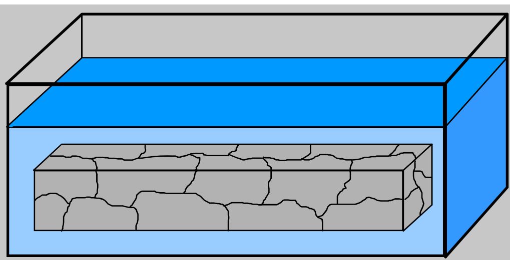
CSA A23.2-25A ASTM C 1260 RILEM AAR-2

Aggregate/cementitious material = 2.25

W/CM = 0.5

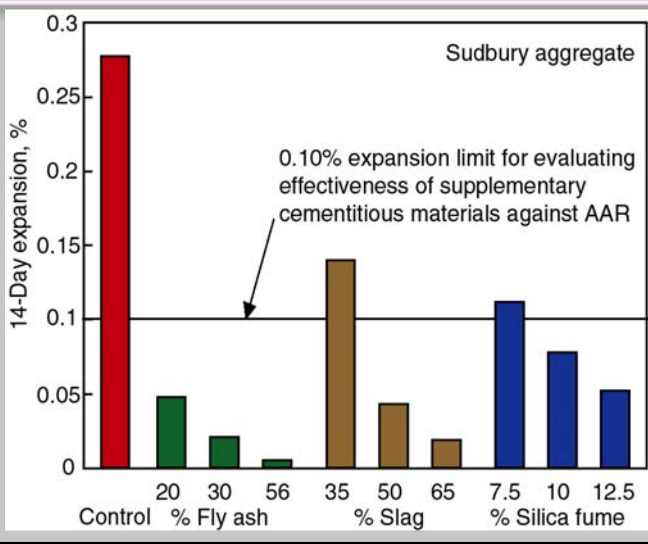
Portland cement = 0.8 to 1.0% Na_2O_e

Mortar bars, 25 x 25 x 250 mm, stored in 1M NaOH at 80°C for **14 days**



35

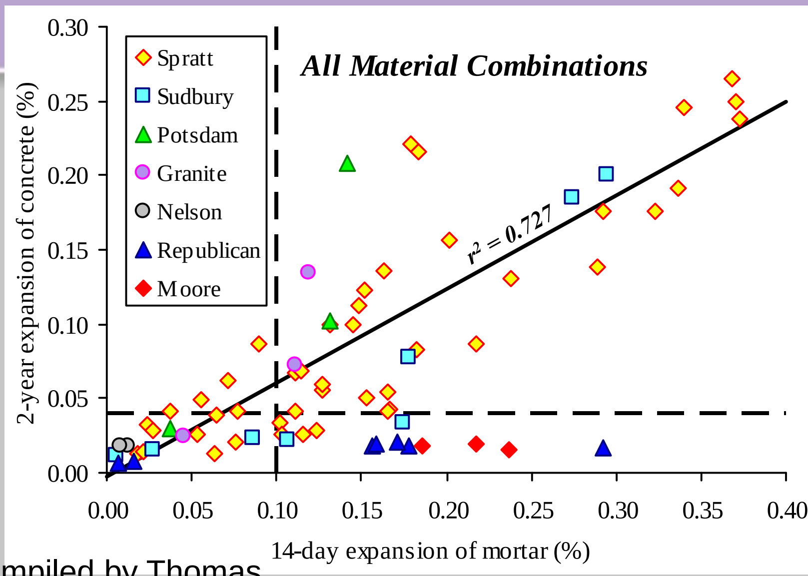
80 °C Mortar Test appears to work for assessing mitigation but should be confirmed by concrete prism data



PCA EB101 (Fournier)

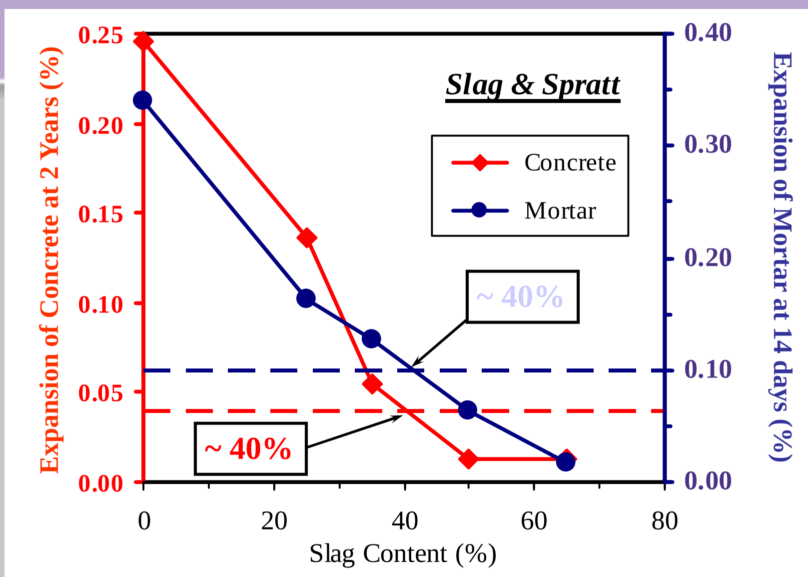
36

Accelerated Mortar Bar vs. Concrete Prism Test



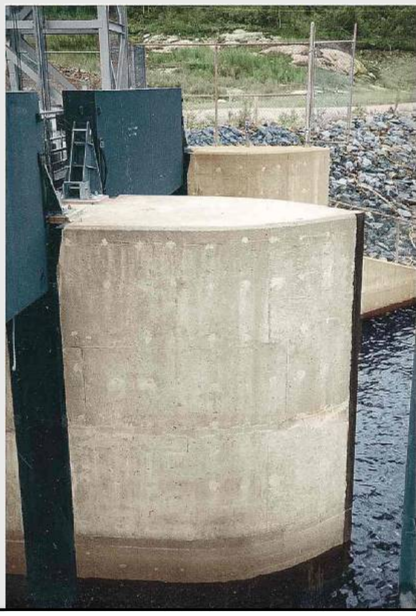
Compiled by Thomas

Expansion Test Results



Steephill Falls Spillway on Magpie River, Ontario

- ***50% Slag Concrete made with ASR aggregate in 1988 is in excellent condition after 20 years.***
- ***There was also no petrographic evidence of any ASR activity after 10 years.***
- ***Note that Concrete was placed during the winter***



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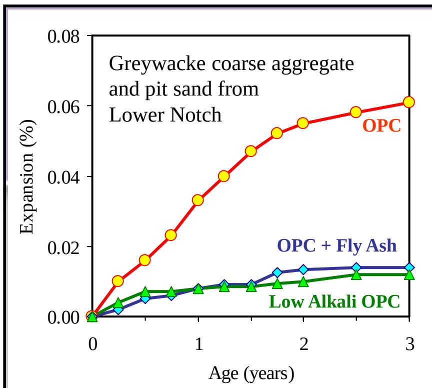
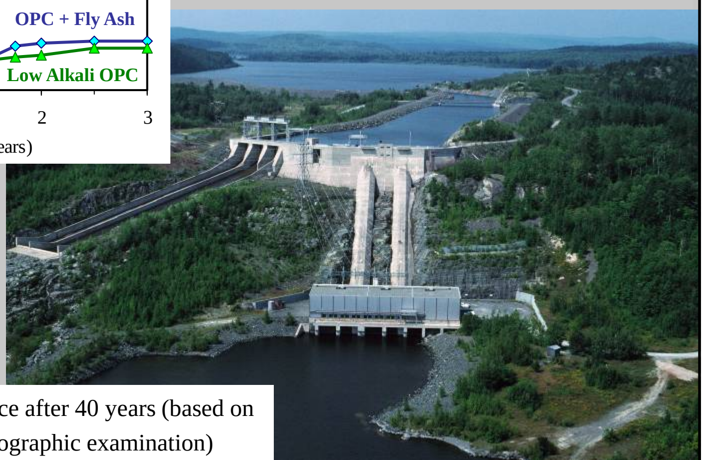
Department of Civil Engineering



Lower Notch Dam, Ontario

20% to 30% fly ash used with high-alkali cement and highly reactive aggregate



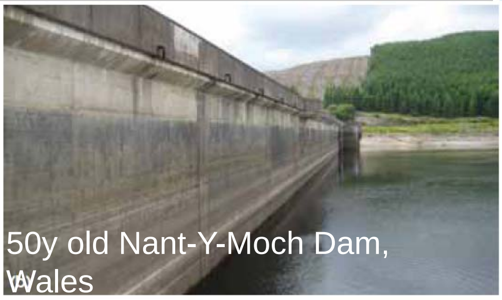
Excellent field performance after 40 years (based on visual inspection and petrographic examination)
(Hooton, Thomas, Rogers, Fournier Site Visit 2010)

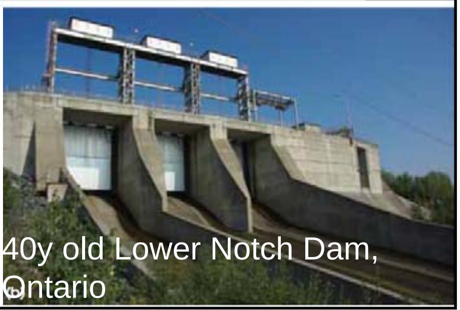
Jan. 2012 Concrete International

50 Years Old and Still Going Strong

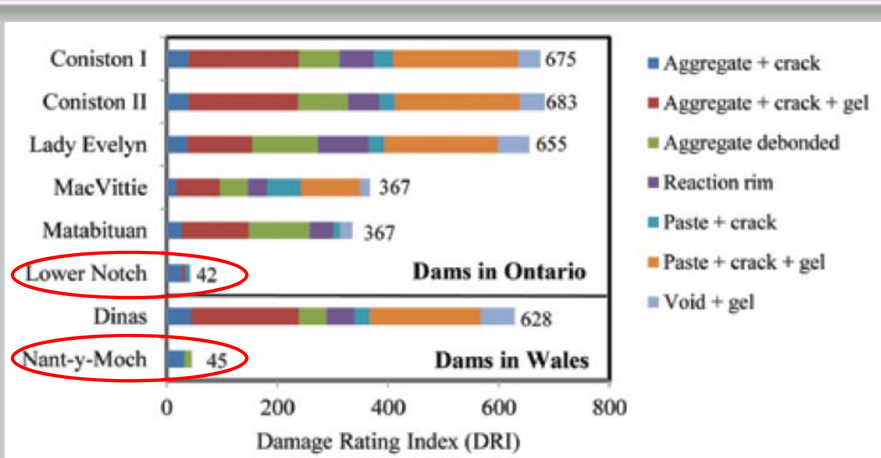
Fly ash puts paid to ASR

by Michael Thomas, R. Doug Hooton, Chris Rogers, and Benoît Fournier


50y old Nant-Y-Moch Dam, Wales


40y old Lower Notch Dam, Ontario

CI Jan. 2012



The 2 dams with fly ash are undamaged and cores exhibit low DRI

Site Established in Kingston, Ontario in 1991

6 different concrete mixtures reinforced and non reinforced blocks and slab for each mix
Spratt coarse aggregate and local non-reactive fine aggregate

Hooton, Rogers, MacDonald, Ramlochan 2012 (in press)

Sept. 1991 Kingston Site

Binder	Mix 1 50% Slag 50% HAPC	Mix 2 18% Fly Ash 82% HAPC	Mix 3 25% Slag 75% HAPC	Mix 4 25% Slag+3.8% SF 71% HAPC	Mix 5 100% LAPC 0.46% Alkali	Mix 6 100% HAPC 0.79% Alkali
w/cm	**0.4**	**0.39**	**0.39**	**0.38**	**0.37**	**0.34**
Alkali Loading (of PC) kg/m^3 Na_2O equiv.	1.64	2.67	2.46	2.34	1.91	3.28

All mixes had total CM = 415 kg/m3

All made with Spratt ASR Coarse Aggregate

(siliceous limestone)

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80°C Spratt Mortar Bar Expansions
CSA A23.2-25A, ASTM C 1260
RILEM AAR-2

Mix #	Binder Type and Proportions	Mortar Bar Expansion in Per Cent: 14 Day	21 Day	28 Day	14 Day Duplicate
1	HAPC, 50% + GGBFS, 50%	0.059	-	-	-
2	HAPC, 82% + fly ash, 18%	0.111	0.171	0.249	0.118
3	HAPC, 75% + GGBFS, 25%	0.187	-	-	-
4	HAPC, 25% + silica fume cement, 75% + GGBFS, 25%	0.041	0.089	0.153	-
5	LAPC, 100%	0.435	0.484	0.553	0.471
6	HAPC, 100%	0.315	0.378	0.480	0.330

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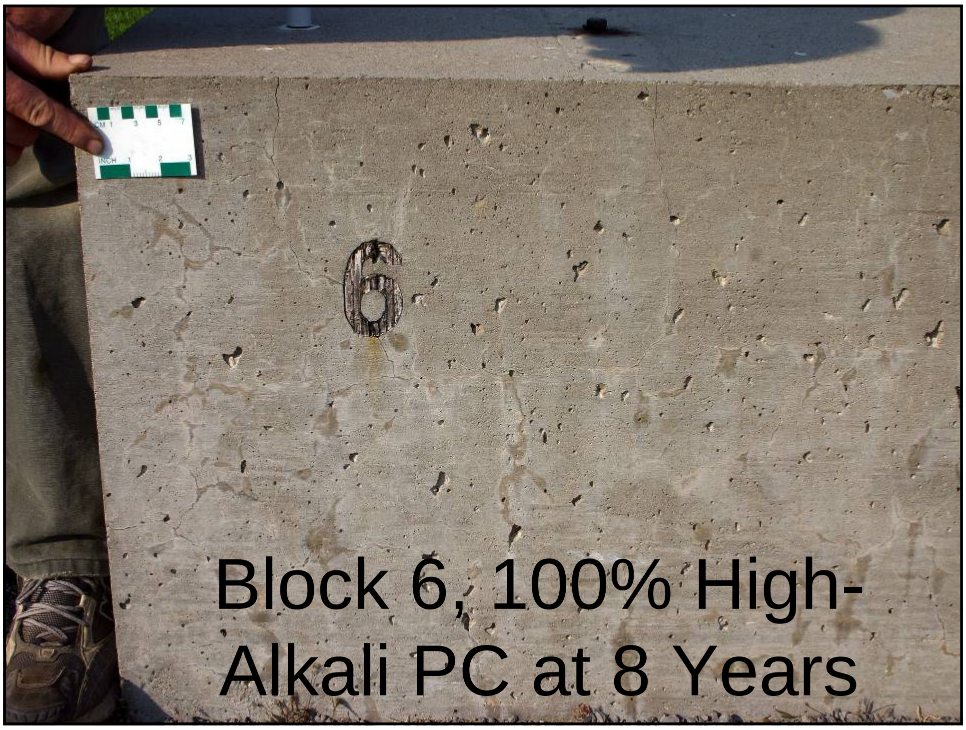
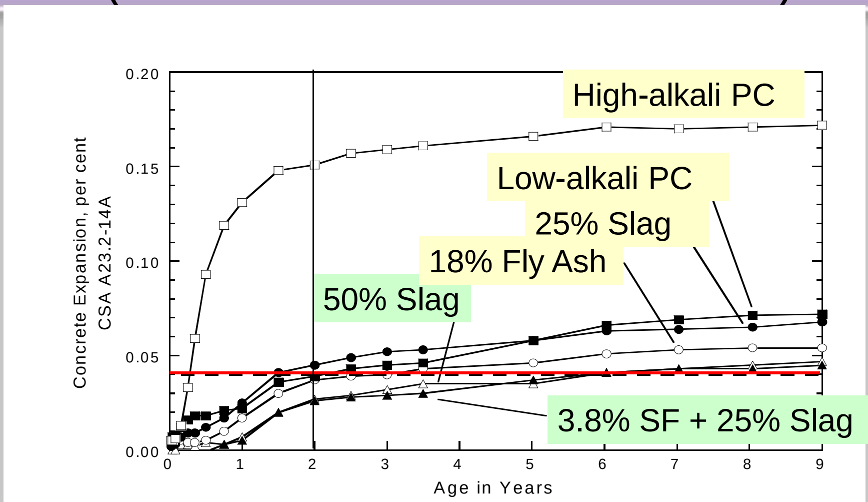
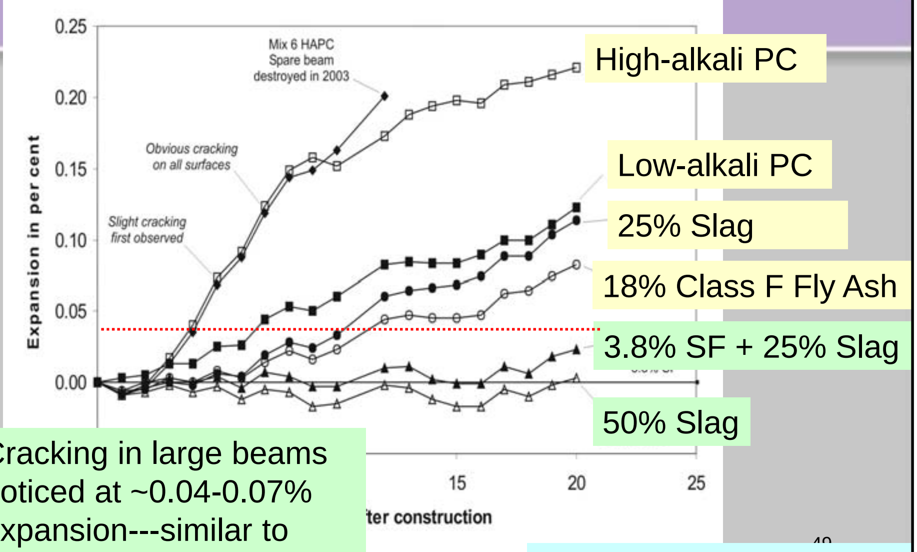


38°C Concrete Prism Expansions to 9 Years (but not boosted to 1.25% alkali)



Inside containers, prisms sealed in bags with 100ml water

16-year old 0.6x0.6x2.0 m concrete beams exposed outdoors in Kingston (mixes: 420kg/m^3)

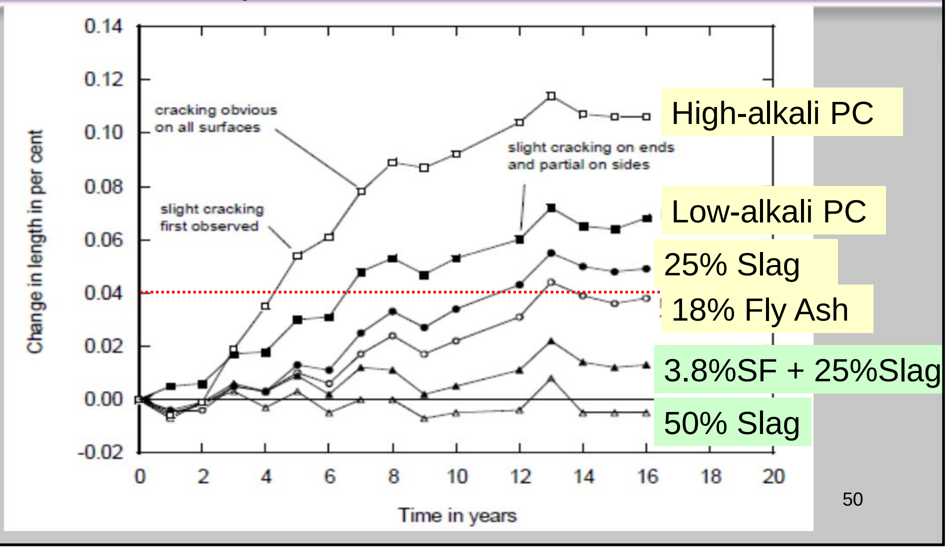


Cracking in large beams noticed at ~0.04-0.07% expansion---similar to 38C concrete prisms

Hooton and Rogers, 2008

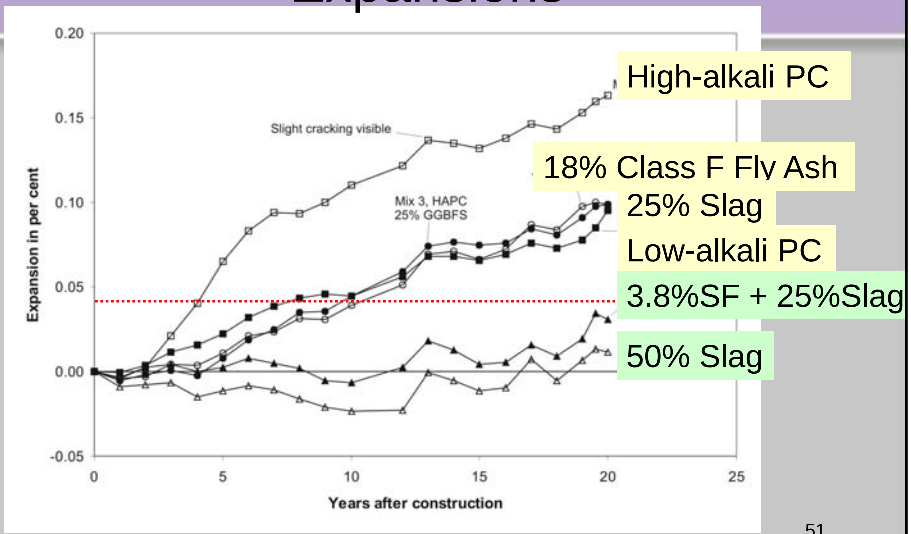
20-year Reinforced Beam Expansions

Area of steel = 1.41%
(4-25M and 8-20M bars



50

20-year Pavement Slab Expansions



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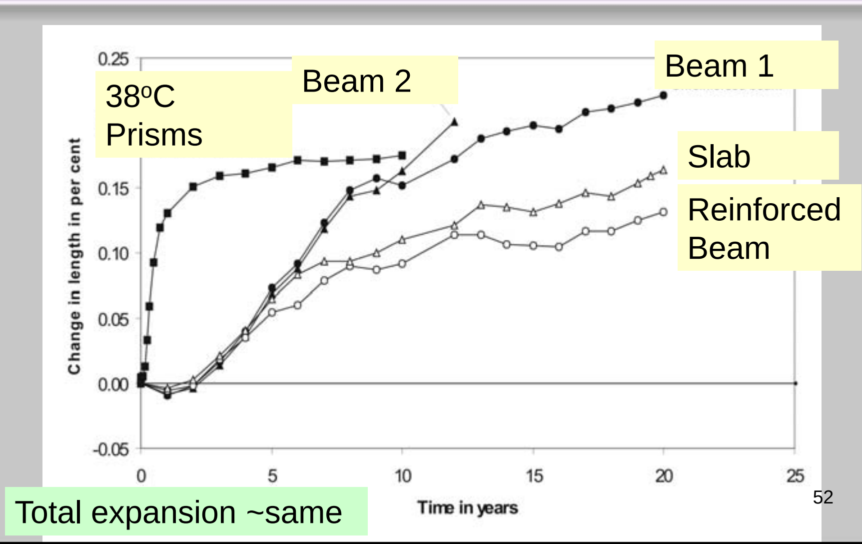
Mix 6: High-alkali Cement Concrete Lab vs 20-Year Field Exp'n



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If you test an aggregate and determine that is alkali-reactive,….

- What are the options?
- I will review the Canadian CSA options.
- Similar approaches have been adopted by AASHTO and are now being considered by ASTM and by RILEM

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A) CSA Allows Performance Testing

© Canadian Standards Association — Test methods and standard practices for concrete

A23.2-28A

Standard practice for laboratory testing to demonstrate the effectiveness of supplementary cementing materials and lithium-based admixtures to prevent alkali-silica reaction in concrete

1 Scope

This Standard Practice describes the procedures to be followed to demonstrate the effectiveness of supplementary cementing materials and lithium-based admixtures or combination thereof, in preventing excessive expansion caused by alkali-silica reaction. The supplementary cementing materials are as defined in CSA A3001.

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C) Risk Minimization: Canadian Guideline for ASR: CSA A23.2-27A (revised 2009)

Allows the use of reactive aggregates with following preventive measures:

- Limiting the alkali content of the concrete
- Use of fly ash
- Use of slag
- Use of silica fume
- Use of ternary blends

The actual level of prevention varies with “risk” as defined by:

- Reactivity of the aggregate
- Nature of the structure (incl. design life)
- Exposure condition

Basis for the CSA A23.2-27A Guide for Risk Minimization

- Pooled concrete prism data from labs across Canada
- Data from Several Field Exposure Sites in Canada and USA.
- Field cases of mitigated ASR (eg. Lower Notch and Magpie River Dams in Ontario)
- Data is being constantly added to update the standard.

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Table 2
Degree of Alkali-Silica Reactivity of Aggregates

Classification of the Degree of Alkali-Silica Reactivity	1-Year Expansion (%) by Test Method C 1293 (see Notes A and C)	14-Day Expansion (%) by Test Method C 1260 (see Notes B and C)
Non-reactive	<0.040 %	<0.10%
Moderately reactive	0.040 - 0.120 %	
Highly reactive	>0.120 %	>0.15%
Extremely reactive	>0.230 %	>0.40%

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Table 3
Determination of the Level of Risk of ASR

Size and concrete environment	Degree of Reactivity of the Aggregate (from Table 2)			
	Non-reactive	Reactive		Extremely
		Moderately	Highly	
Non-massive and dry (see Notes A and B)	Level 1	Level 1	Level 2	Level 3
Massive and dry (see Notes B and C)	Level 1	Level 2	Level 3	Level 4
All concrete exposed to humid air, buried or immersed (see Note D)	Level 1	Level 3	Level 4	Level 5

Note A: A "massive" element has a least dimension of one meter or more.
Note B: A dry environment corresponds to ambient average relative humidity condition lower than 60%, normally only found in internal structural elements of buildings.
Note C: A risk of alkali-silica reaction exists for massive concrete elements in a dry environment because the internal concrete has a high relative humidity.
Note D: A non-massive concrete element constantly immersed in sea water does not present a higher risk of ASR than a similar element exposed to humid air, buried in the ground, or immersed in pure water because the alkali concentration of sea water (30 g/L NaCl >0.51 M NaCl or Na) is lower than the alkali concentration of the pore solution of most concrete.

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Table 4
Level of Prevention

ASR Risk level from Table 3	Temporary Elements (<5 years)	Required Service Life of 5 to 75 years	Required Service Life of greater than 75 years
1	V	V	V
2	V	W	X
3	V	X	Y
4	W	Y	Z
5	W	Z	ZZ

V = Accept for use without any preventive measure.
W, X, Y, Z = Preventive measures are required (see Table 5).

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Table 6 Use of SCMs for counteracting alkali-silica reaction

‡ need to test using CSA A23.2-28A

Type of SCM	Total alkali content of SCM % Na2Oeq	Chemical requirement (% oxides)	Cement replacement level (% by mass) Prevention level W	Prevention level X	Prevention level Y	Prevention level Z
Fly ash	<3.0	CaO < 8%	15	20	25	35
		CaO = 8%–20%	20	25	30	40
		CaO > 20%	‡	‡	‡	‡
	3.0–4.5	CaO < 8%	20	25	30	40
		CaO = 8%–20%	25	30	35	45
		CaO > 20%	‡	‡	‡	‡
	>4.5	‡	‡	‡	‡	‡
Blast-furnace slag	<1.0	None	25	35	50	60
Silica fume	<1.0	None	2.0 × Alkali content	2.5 × Alkali content	3.0 × Alkali content	‡

Table 6 (d) TERNARY BLENDS

When two, or more, SCM's are used together to control ASR, the minimum replacement levels given in Table 6 for the individual SCM's may be partially reduced provided that the sum of the parts of each SCM is greater than, or equal to, one. For example: when silica fume and slag are combined, the silica fume level may be reduced to one third of the minimum silica fume level given in Table 6 provided that the slag level is at least two thirds of the minimum slag level given in Table 6.

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Conclusions

- **The effectiveness of silica fume, fly ash or blast-furnace slag in controlling ASR expansion is related to the ability of these SCMs to reduce pore solution alkalinity and maintain its depressed levels over time.**
- **These binders have lower Ca/Si C-S-H which promotes alkali binding**
- **Fly Ash, Slag and SF-ternary binders also have more Al in the C-S-H, which also promotes alkali binding**
- **The CSA Guide uses knowledge gained from all available lab and field data to allow design based on risk minimization.**

The Norwegian System for Performance Testing of Alkali-Silica Reactivity (ASR) – Some Experiences

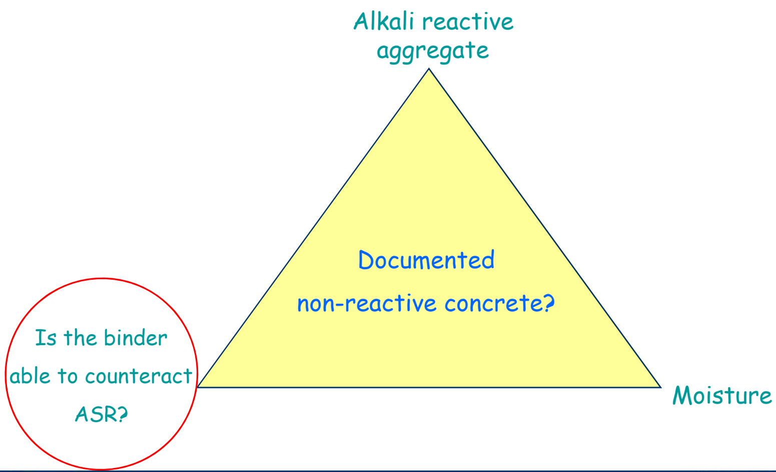
Jan Lindgård (SINTEF)

Co-author:
P.A. Dahl (SINTEF)

SINTEF Building and Infrastructure 1

What is "performance testing"?

= pre-documentation of binders or concrete recipes in the laboratory



SINTEF Building and Infrastructure 2

Background

- Alkali reactive aggregates are present in most parts of Norway
  - ✓ How should we utilize these aggregates safely in concrete?
- ASR performance testing have been included in the Norwegian regulations for 15 years
  - ✓ Has been frequently used (> 175 test series)
  - ✓ Are our test procedures and system for approval reliable?
- Research is going on world wide with an aim to develop one or more reliable performance test methods
  - ✓ e.g. within RILEM TC 219-ACS (2007-2012)
  - ✓ PhD study within COIN (2007-2012)

SINTEF Building and Infrastructure 3

The Norwegian system for performance testing

- Regulations: Norwegian Concrete Association (NB) publ. no. 21: "NB21"
  - ✓ Published in 1996
    - Voluntary approval arrangement
  - ✓ Revised in 2004
    - Normative reference to NS-EN 206-1
- Applications of the Norwegian performance test
  - ✓ Alkali threshold for an aggregate combination
  - ✓ Alkali threshold for a binder (e.g. blended cement)
    - Reference "worst case" alkali reactive aggregates applied
  - ✓ Actual concrete recipes ("job-mixes")

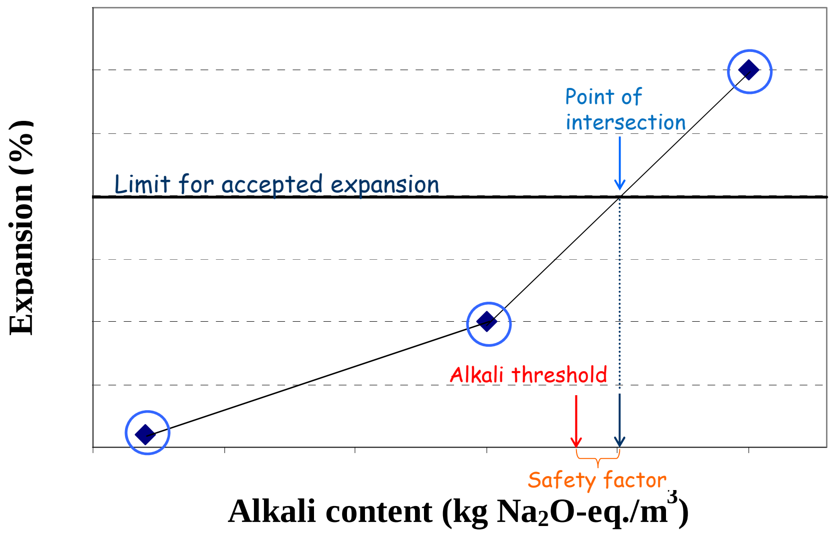
SINTEF Building and Infrastructure 4

- Performance test method applied in Norway for 15 years: **Norwegian 38°C CPT**
  - ✓ Prism size:
    - cross-section: 100·100 mm^2
    - length: 450 mm
  - ✓ 100 % RH
    - prisms stored on a grid, above water
  - ✓ 38°C (heated room)
  - ✓ Exposure time: 1-2 years
    - Dependent on type of binder
  - ✓ Measurements
    - Expansion
    - Weight increase (QC)

The Norwegian system for performance testing

- **Ambition**
  - ✓ Stop approx. 95 % of potential harmful concrete recipes
    - Same security level as other deterioration mechanisms
    - Avoid stopping too many non-reactive concrete recipes
- **Validity**
  - ✓ The documentation from performance testing is valid as long as the reactivity of the concrete is not increased
  - ✓ The reactivity of the concrete is considered to increase if:
    - Increased alkali content (but more of the pozzolanic material may be added)
    - Decreased content of pozzolanic material or other SCMs
    - Increased content of reactive rock types (beyond a specified limit)

Principle for determination of alkali threshold
(aggregate comb. or binder)

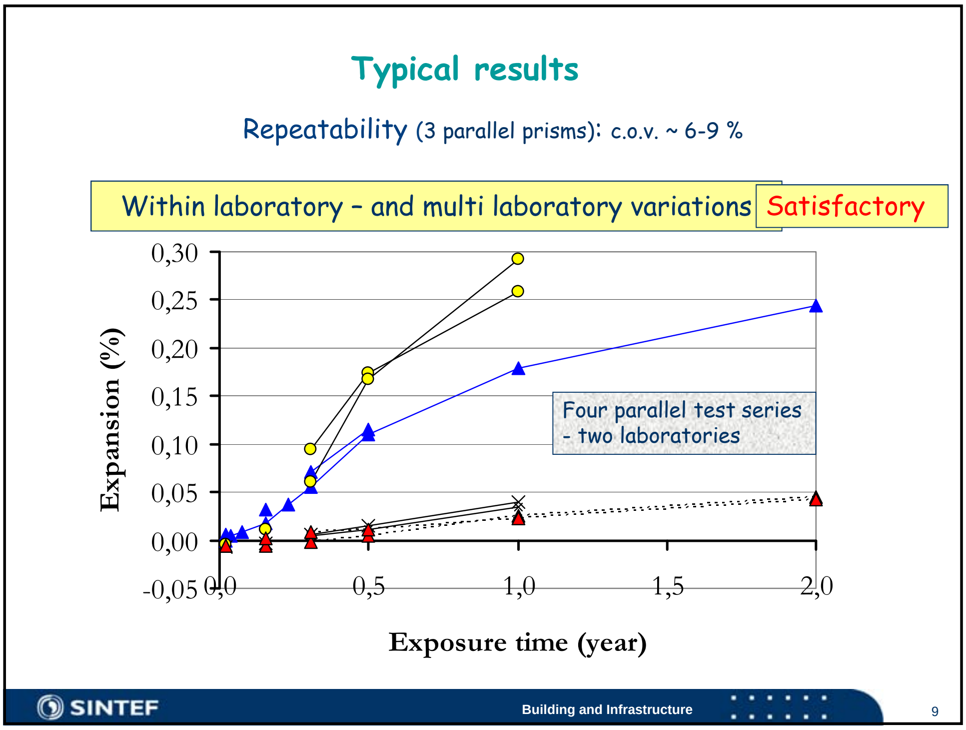


SINTEF Building and Infrastructure 7

Review of experiences

- About 150 test series have recently been reviewed
  - ✓ Lindgård et al. (ICAAR 2008, NCR 2010)
    - About 45 % contain fly ash binder
    - About 20 % include silica fume
    - About 15 % include fillers with possible pozzolanic effect (PhD-thesis Bård Pedersen)
    - Less than 3 % contain slag (ggbfs) cement

SINTEF Building and Infrastructure 8


Typical results
Repeatability (3 parallel prisms): c.o.v. ~ 6-9 %
Within laboratory - and multi laboratory variations
Satisfactory
Expansion (%)
0,30
0,25
0,20
0,15
0,10
0,05
0,00
-0,05
0,0
0,5
1,0
1,5
2,0
Four parallel test series - two laboratories
Exposure time (year)
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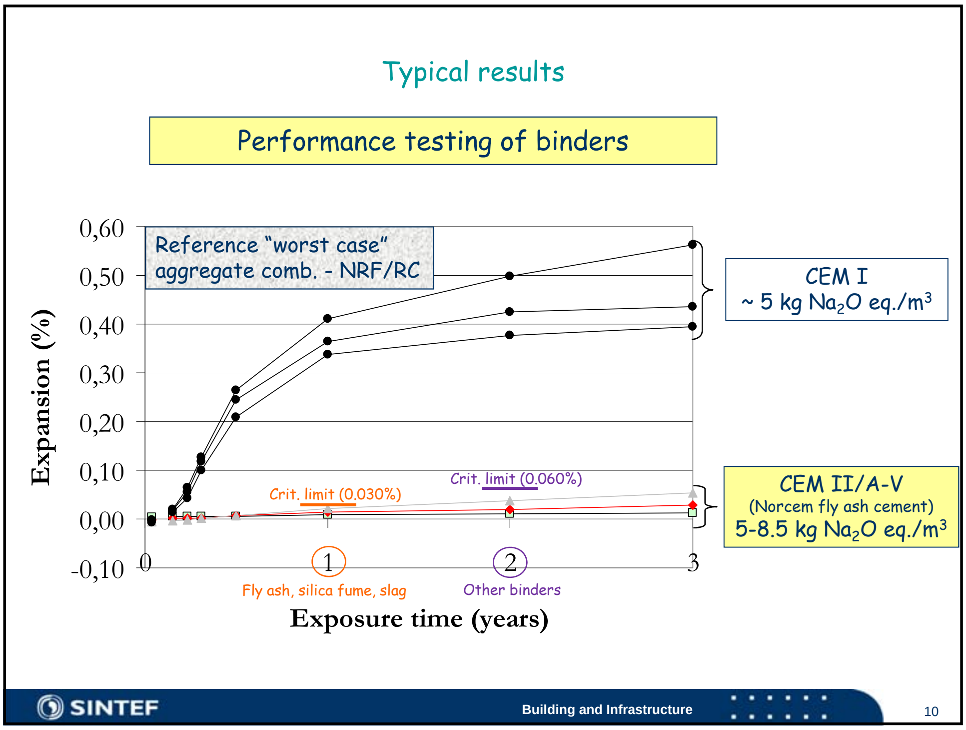
Typical results
Performance testing of binders
Reference "worst case" aggregate comb. - NRF/RC
CEM I
~ 5 kg Na2O eq./m3
CEM II/A-V
(Norcem fly ash cement)
5-8.5 kg Na2O eq./m3
Expansion (%)
0,60
0,50
0,40
0,30
0,20
0,10
0,00
-0,10
Crit. limit (0,030%)
Crit. limit (0,060%)
0
1
2
3
Fly ash, silica fume, slag
Other binders
Exposure time (years)
SINTEF
Building and Infrastructure
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Documentation of binders – available for all concrete producers

- NB21, appendix C
  - ✓ List of all "safe binders" documented is available at the web-page of NCA – updated continuously
    - The documentation is valid for all types, amounts and combinations of Norwegian aggregate types (included all the alkali reactive ones)
  - ✓ Crucial important for exploitation of Norwegian aggregate resources
    - Long distance transport of aggregates is costly and not environmental friendly
    - Aggregate and concrete producers do not have to document their materials separately (unless they will try to document a higher alkali limit than approved for all Norwegian aggregate types)

SINTEF Building and Infrastructure 11

Documentation of binders – available for all concrete producers

- Example (NB21, appendix C, Table C1):

Maximum allowed alkali content (included all alkalis in the SCM) for the manufacture of non-reactive concrete containing all types, amounts and combinations of Norwegian alkali reactive aggregates:

Binder	Limit value, alkali-content (Na_2O-eq.)
Norcem Standard FA cement from plant Kjøpsvik [CEM II/A-V, NS-EN 197-1, fly ash content > 17 %]	< 7.0 kg/m³
Norcem Standard FA cement from plant Brevik [CEM II/A-V, NS-EN 197-1, fly ash content > 17 %]	< 6.5 kg/m³
Embra miljøsement [CEM II/B-S, NS-EN 197-1, slag content ≥ 32 %]	< 4.0 kg/m³

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Reliable test method – but not the ideal one ...(?)...

- Challenge no. 1: **Duration of the test (1-2 years)**
  - ✓ Hardly any "job mixes" tested
  - ✓ Very relevant for an aggregate – or concrete producer to determine the alkali threshold for their aggregates, despite the long testing time
  - ✓ Cement producers frequently test new binders, but some problems have occurred
    - Change in supplier of fly ash ⟹ new documentation required

SINTEF Building and Infrastructure 13

- Challenge no. 2: **Leaching of alkalis**
  - ✓ If too much alkali leaching ⟹ unreliable alkali thresholds
    - Debated internationally
  - ✓ Some extra security are, however, built in the Norwegian regulations
    - "Worst case" reactive aggregates applied when testing binders (far more reactive than most Norwegian aggregates in common use)
    - Most commercial concretes containing SCMs will normally contain less alkalis than the critical alkali limits documented for various binders
    - Norcem have also declared "upper alkali limits" for their cements to be used for calculating the concrete alkali content according to the Norwegian regulations
  - ✓ Alkali leaching is being extensively investigated in the PhD study
    - Norwegian CPT compared with three RILEM CPTs and ASTM C-1293

SINTEF Building and Infrastructure 14

Some conclusions

- Despite the duration of the test (1-2 years), the Norwegian system for performance testing has proven to be an advantageous and flexible tool for the Norwegian concrete industry to document alkali thresholds for binders and aggregates
- The Norwegian system for performance testing is regarded to be at least as safe as the regulations to prevent rebar corrosion and frost damage

SINTEF Building and Infrastructure 15

Some conclusions

- By using the Norcem Standard-FA cement (incl. ≥ 17 % fly ash) a general acceptance alkali limit of 6.5 (or 7.0) kg Na_2O eq./m^3 are approved in combination with all Norwegian aggregate types in common use
- The possible influence of alkali leaching on the measured expansions in our Norwegian CPT can not be neglected
  - ⇨ currently an issue for research internationally (e.g. RILEM)
  - ⇨ part of my PhD study (2007-2012)

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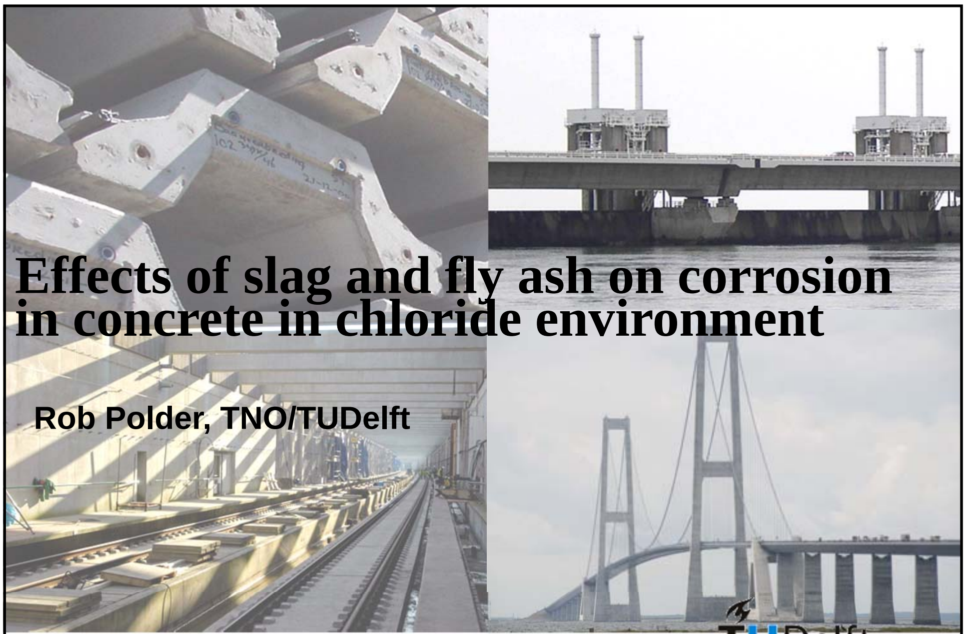


Effects of slag and fly ash on corrosion in concrete in chloride environment

Rob Polder, TNO/TUDelft

TUDelft
TNO innovation for life

introduction

- Netherlands: slag in cement from 1930s
- CEM III/B LH HS c. 70% slag market leader >1970
- 10 million m^3 slag concrete per year!
- fly ash since 1980s, CEM II/B-V 32.5
- both: sold as *cement,* equal strength @ 28 days
- c. 2000: CEM III/A 52.5 R, 57% slag for precast
- typical technology 340 kg/m^3 w/c 0.43, rounded siliceous aggregate, 32 mm
- experience, research, focus on NL!

TUDelft
TNO innovation for life

durability in the field; *slag*

- 1980 Wiebenga, 50 marine structures up to 40 years age: corrosion is rare
- 1996 Polder & Larbi prisms 16 year submerged in North Sea, chloride penetration much lower than OPC, *higher resistivity* →
- 2005 Polder & De Rooij 6 marine structures, chloride profiles, cover depth!
- 1 case of corrosion with slag (low cover, quality) →

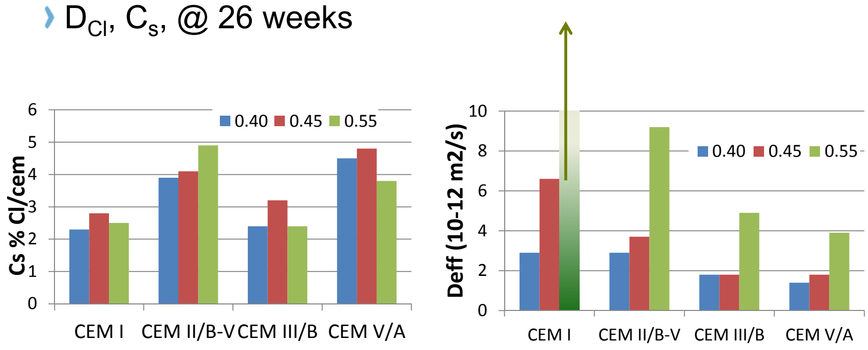
XS3, effective D_{Cl} after *n* years * 10^{-12} m^2/s; C_s

ref	CEM I	CEM III/B	*n* year, type	C_s % cement
Polder & Larbi 1996	1 - 3 (~w/c, start!)	0.3	16, subm. prisms	#
Polder & De Rooij 2005	0.14/0.28 (sheltered)	0.33	40, pier	~ 3
	-	0.12-0.19	20-33, 3 quays	3-4
	-	0.12	40, barrier	2.8
	-	0.24	20, barrier	2.2 (..5)

2.5 – 5, ~ start exposure

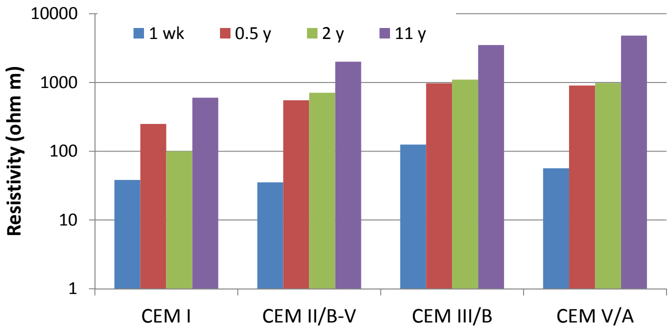
Cl transport & Resistivity

- 1998 Salt/dry (1/6 day, 26 weeks); CEM, w/b
- D_{Cl}, C_s, @ 26 weeks



TU Delft
TNO innovation for life

- resistivity 1998 until 2010 (outside)
- 28 day CEM III/B > others
- mature CEM III/B ≅ CEM V/A > CEM II/B-V > CEM I
- CEM II/B-V 27 % fly ash: increase 2 – 6 months!

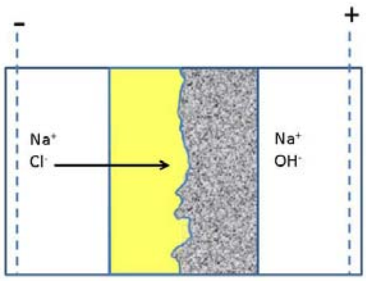


TU Delft
TNO innovation for life

2000s: new test method (Tang et al.)

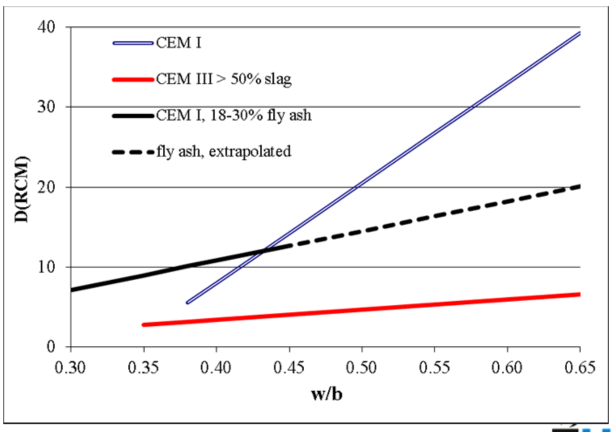
- accelerated transport potential field: *migration*
- rapid chloride migration, RCM, NT Build 492
- 10-60 V; 1- 4 days, $AgNO_3$, calculate D_{RCM}

- analysis 500+ results
- cement, w/b, 28d – 3 year



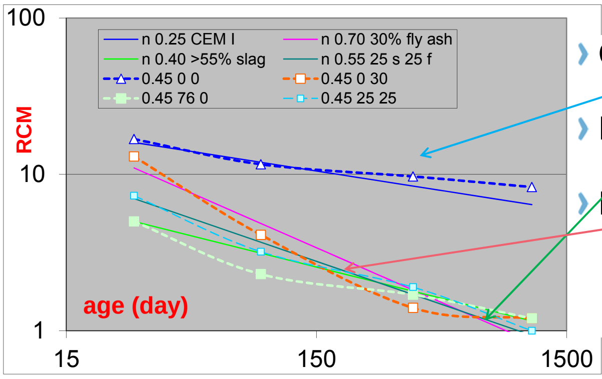
TNO innovation for life

- D_{RCM} (28 day) = A*w/b + B
- A, B f(binder)



TUDelft
TNO innovation for life

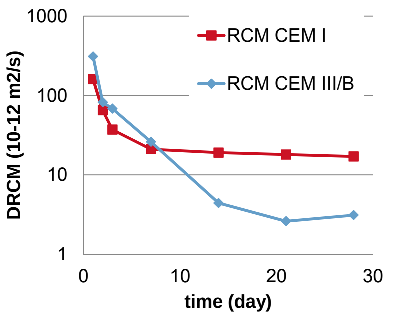
- D_{RCM} = f(time, CEM) = $D_0 * (t_0/t)^n$
  t 28 d – 3 y; n?

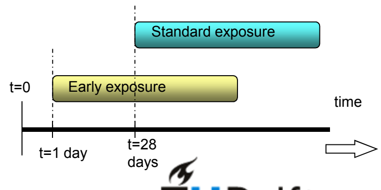


- CEM I n~ 0.25
- III >50% s n~ 0.4
- II 30% f n~ 0.7

slag and chloride at young age

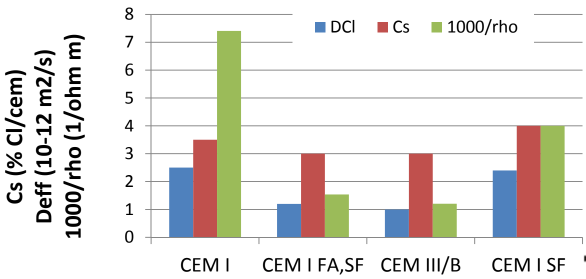
- Caballero, MSc 2009
- CEM I, III/B mortar w/b 0.50
- D_{RCM} at 1, 2, 3, 7, 14, 28 day
- Early $D_{slag} > D_{OPC}$
- from 7 days on $D_{OPC} > D_{slag}$
- Resistivity corresponding
- CEM III/B after 50 years: start exposure @ 1 day 1.4 mm deeper penetration than @ 28 d.. (t_{ini} - 4 years)
- .. cure with sea water?





fly ash, silica fume

- 1990s 'new concrete mixes' for marine application..
- CEM I; 5% sf & 10% fly ash; CEM III/B; 5% silica fume
- 340 kg/m^3 cement, w/b 0.43, D 16 mm
- immersion 3.5% NaCl 4 – 24 months (~NTBuild 443)
- 30 C! Cl profiles fitted, D_{eff}, C_s 20 C resistivity (rho)

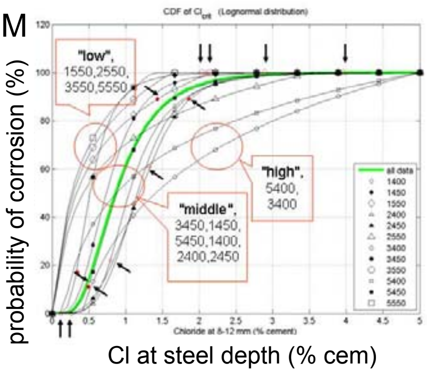


TU Delft

TNO innovation for life

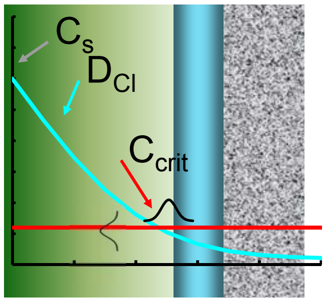
critical chloride content..

- literature: no effect of cement type (effect of w/b!)
- experiment: 26 weeks salt/dry cycles
- chloride profile, E_{steel}, Corrosion Rate
- slag (fly ash, both): lower CR than CEM I at same Cl
- statistical analysis E_{steel}
- prob of corr: f w/b, not CEM



- 1 CEM I, 3 CEM III..
- 55 w/b 0.55 ..

overview and conclusions



- Practice: >50 year 70% slag cement
- C_s same as Portland
- D_{Cl} lower, n(time), resistivity higher
- C_{crit} same

- Fly ash (20-30%) roughly similar as slag

- early age: slag OK (> 7 days); fly ash slow (> 60 d)

- slag & fly ash (Σ 50%): similar as 70% slag (slower)

- chloride, corrosion: slag (fly ash) better performance!

Business from technology

The effect of slag and fly ash on interaction of chloride penetration and carbonation

Nordic Workshop on
Durability aspects of fly ash and slag in concrete

Hannele Kuosa
VTT Technical Research Centre of Finland

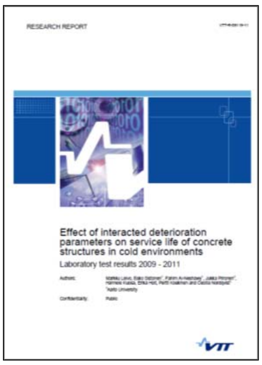
Contents

Background information

DuraInt-project testing results – mixes with +FA/+BFS and Reference

1. Effect of fully carbonated concrete on Cl-migration
2. Effect of surface carbonation on Cl-migration
3. Effect of chlorides on carbonation
4. (Release of fixed chlorides – no results here)

Summary


RESEARCH REPORT

Effect of interacted deterioration parameters on service life of concrete structures in cold environments

Laboratory test results 2009 - 2011

Detailed information in DuraInt-project Task 3 report:
“Laboratory test results 2009 – 2011”
http://www.vtt.fi/sites/duraint/index.jsp

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DuraInt –project reports (Task 1 – Task 6):
http://www.vtt.fi/sites/duraint/index.jsp
Including e.g.:

- Field- and laboratory testing results,
- Deterioration and service life modelling
- Excels including field testing results for different projects & fields
    - DuraInt, BTB, CONLIFE, YMP-YST

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Background: Chloride-carbonation interaction - with +FA/+BFS

+ Effect of +FA and +BFS on migration coefficient (D_{nssm})

+ Penetration of chlorides into non-carbonated concrete - can be expected to degrease with the use of BFS/FA

- Effect of carbonation & drying on chloride penetration - with +FA/+BFS
    - effects on the pore structure - coarsening of the pore structure
    - effect of +FA/+BFS in comparison with no additions (OPC)

+ Effect of chlorides on the rate of carbonation - with +FA/BFS
    - Chemical changes - chemically bound chlorides
    - Effects of free chlorides - hygroscopy >> degrease of CO_2-diffusion >>degrease of carbonation
    - Change of physical properties by carbonation – cement quality, amount of +FA/+BFS

- Effect of liberation of bound chloride due to carbonation
    - Effect of +FA/+BFS on carbonation depth >> more free chlorides after carbonation >> larger Cl-concentration gradient (more penetration but also outward flow)
    - Increase of moisture content by free chlorides (hygroscopy) >> degrease of CO_2 –diffusion

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In all, the overall long term effect of combined carbonation-chloride exposure must be based on studies, and modeling, considering

- Type of combined carbonation-chloride exposure and
  - Submerged – no carbonation
  - Cyclic drying-wetting – includes carbonation
- All mix design and binding material aspects - OPC/+FA/+BFS
- In DuraInt-project :
  - Task 3: Laboratory test results on chloride-carbonation interaction
  - Only tentative ways for modeling chloride-carbonation interactions (Task 5: Service life)

http://www.vtt.fi/sites/duraint/index.jsp

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(DuraInt-project – Laboratory test results)

1. Effect of fully/through carbonated concrete on chloride migration

Mixes (concrete)

Short code	Cement type	Weff/(Cement +0,80×BFS +0,40×FA)	Binder materials [kg/m³] Cement	BFS	FA	Total effective water [kg/m³]	Aggre-gates Total [kg/m³]	Air content (fresh concrete) [%]	Compressive strength [MPa] 7d	28d
Y05A2	CEM II/A-M(S-LL) 42.5 N	0,51	333	0	0	170	1899	1,4	42,8	57,4
Y05A5	CEM II/A-M(S-LL) 42.5 N	0,51	333	0	0	170	1844	4,4	36,9	50,8
R-BFS05A2	CEM II/A-LL 42.5 R & 50% Blast Furnace Slag	0,50	240	120	0	168	1888	2,2	43,5	66,8
R-FA05A2	CEM II/A-LL 42.5 R & 24% Fly Ash	0,50	300	0	72	165	1885	2,5	47,1	64,9
SR05A2	CEM I 42.5 N	0,50	321	0	0	160	1965	2,0	45,8	62,7

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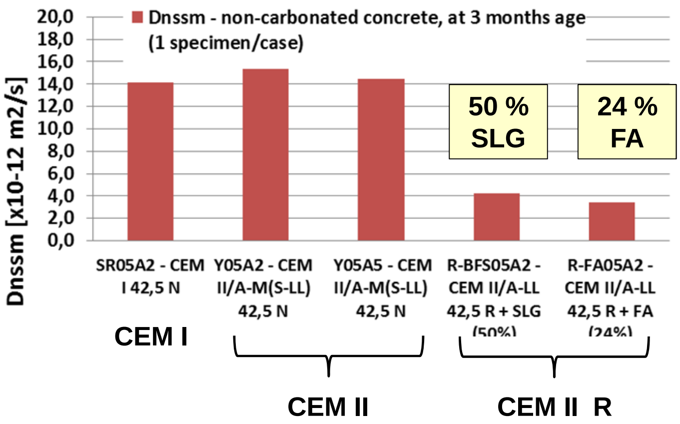
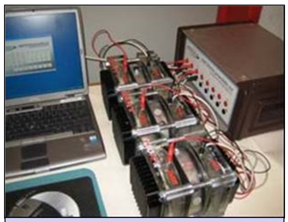
First:

D_{nssm} for non-carbonated concrete

(age 3 months, a´ 3 specimens)





NT Build 492
(CTH-method)

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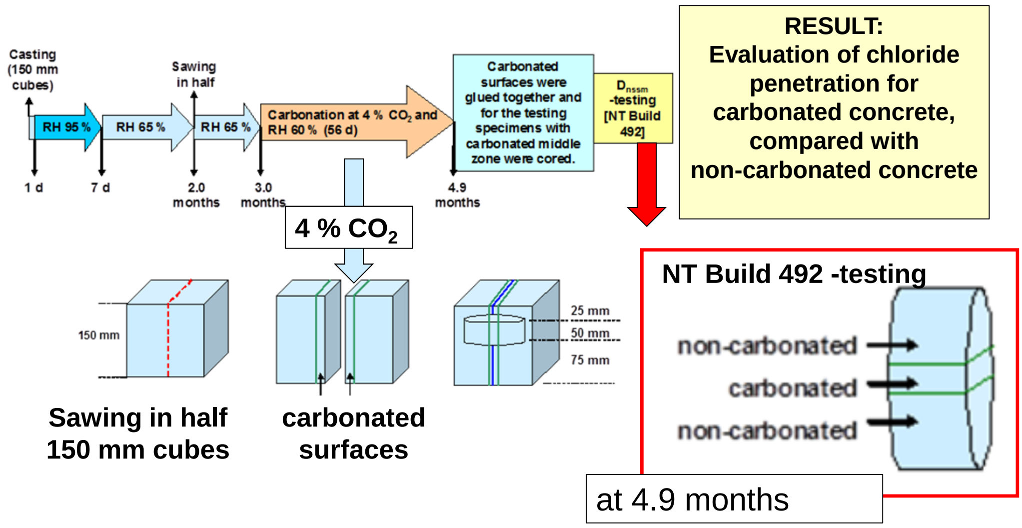
Chloride migration testing (NT Build 492) with fully carbonated middle part in the chloride migration testing



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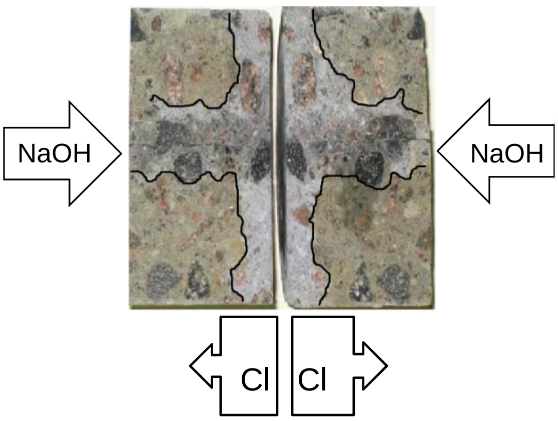
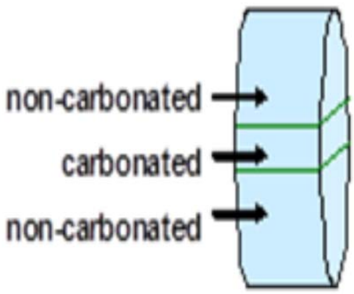
E.g. for concrete with CEM II/A-LL 42.5 R and 24 % FA chlorides had clearly penetrated more through the carbonated middle zone than through the non-carbonated specimen side areas





Split specimen surfaces with the carbonated middle zone after silver nitrate treatment

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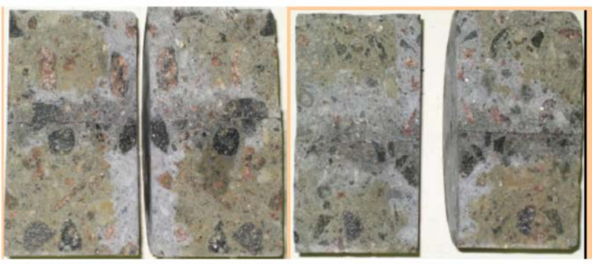
- No numeric D_{nssm} - values for carbonated concrete
- Photos for all the mixes (split specimen surfaces)

(DuraInt Task 3 report: http://www.vtt.fi/sites/duraint/index.jsp)

Carbonation chamber



>> Further testing with mortars and with carbonated specimen surface layer >>>

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(DuraInt-project – Laboratory test results)

2. Effect of carbonated surface layer on chloride penetration and D_{nssm} - effect of FA/BFS

Mixes (mortars, aggregate < 2 mm)

Short code	Cement type	Binder materials [kg/m³]			Total effective water [kg/m3]	Aggregate [kg/m³]		Air content (fresh mortar) [%]	Compressive strength at 28d
		Cement	BFS	FA		R 0-1 mm	R 1-2 mm		
Y05A2	CEM II/A-M(S-LL) 42.5 N	576	0	0	290	920	395	4,1	43,2
Y-BFS05A2		440	220	0	299	858	368	3,4	52,3
Y-FA05A2		542	0	130	304	835	358	4,6	45,5

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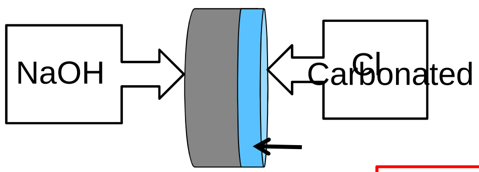
Testing with carbonated surface layer (A) and reference with no carbonation (B)

D_{nssm} -testing NT Build 492:

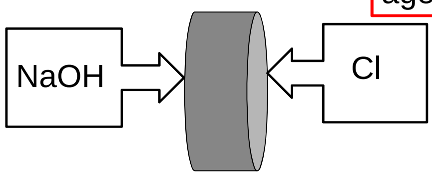
A)
Carbonation:
2 months at RH 65 %
+ 5 months at 4 % CO_2



A) with carbonated surface layer (~5…8 mm)

age 8 months

B)
No surface carbonation (RH 65 %)



B) no surface carbonation

Detailed: DuraInt – Task 3 - Laboratory testing report
http://www.vtt.fi/sites/duraint/index.jsp

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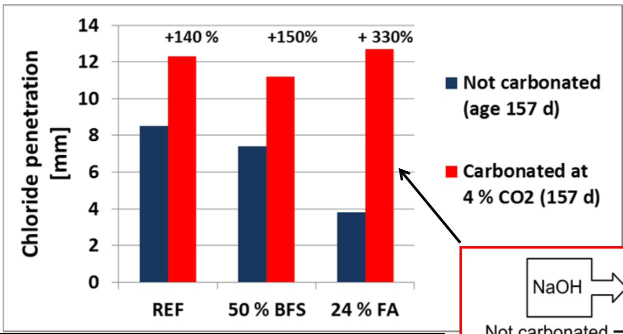
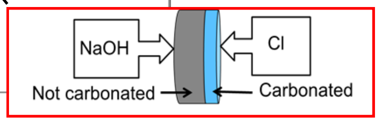
Effect of carbonated skin surface layer on chloride penetration





Applied voltage [V]	30	60	60
Test duration [h]	3,5	10	6
Carbonation [mm]	8,1	4,9	8,4

Obs! No comparision of the mixes here
- different voltages and test durations, and carbonation depths

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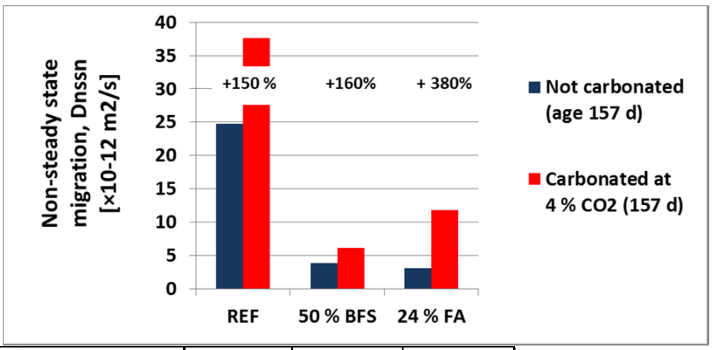
Effect of carbonated surface layer on non steady state migration coefficient D_{nssm} (NT Build 429)



Applied voltage [V]	30	60	60
Test duration [h]	3,5	10	6
Carbonation [mm]	8,1	4,9	8,4

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Surface carbonation increased the depth of chloride penetration achieved by the migration test (NT Build 492)
- The relative increase was more for mixes with added BFS and FA

Also non steady state migration coefficient, D_{nssm}, increased when there was surface carbonation
- The relative increase was more for mixes with added BFS and FA

Still migration coefficient (D_{nssm}) for mixes with FA and BFS was always lower than for the reference

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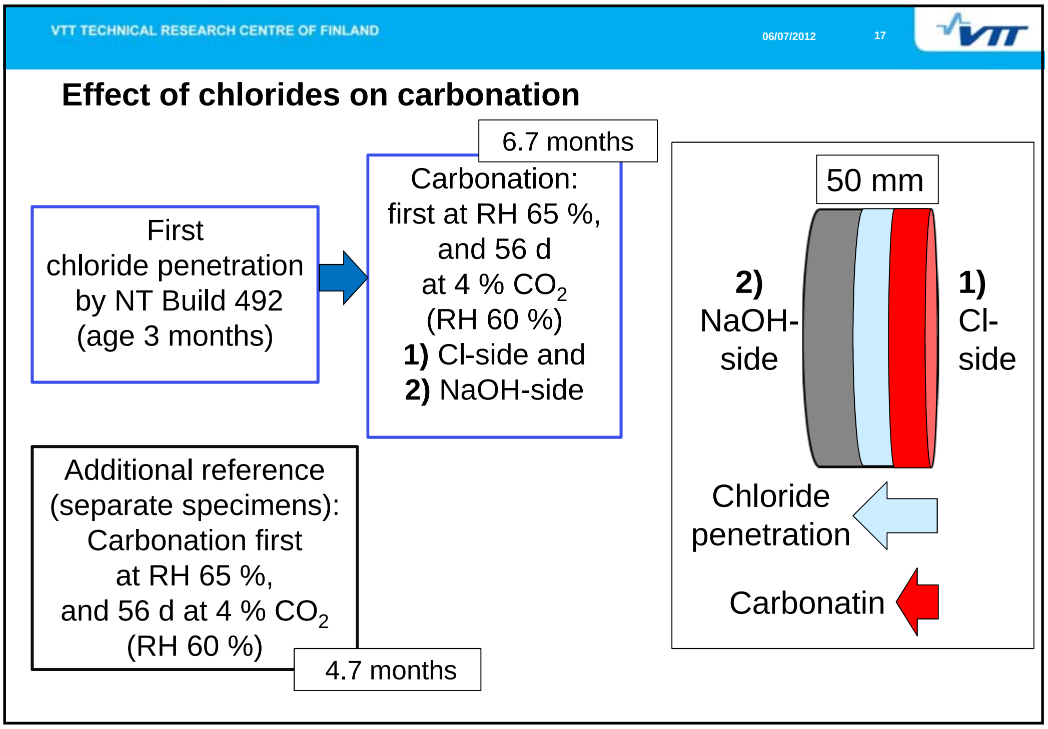
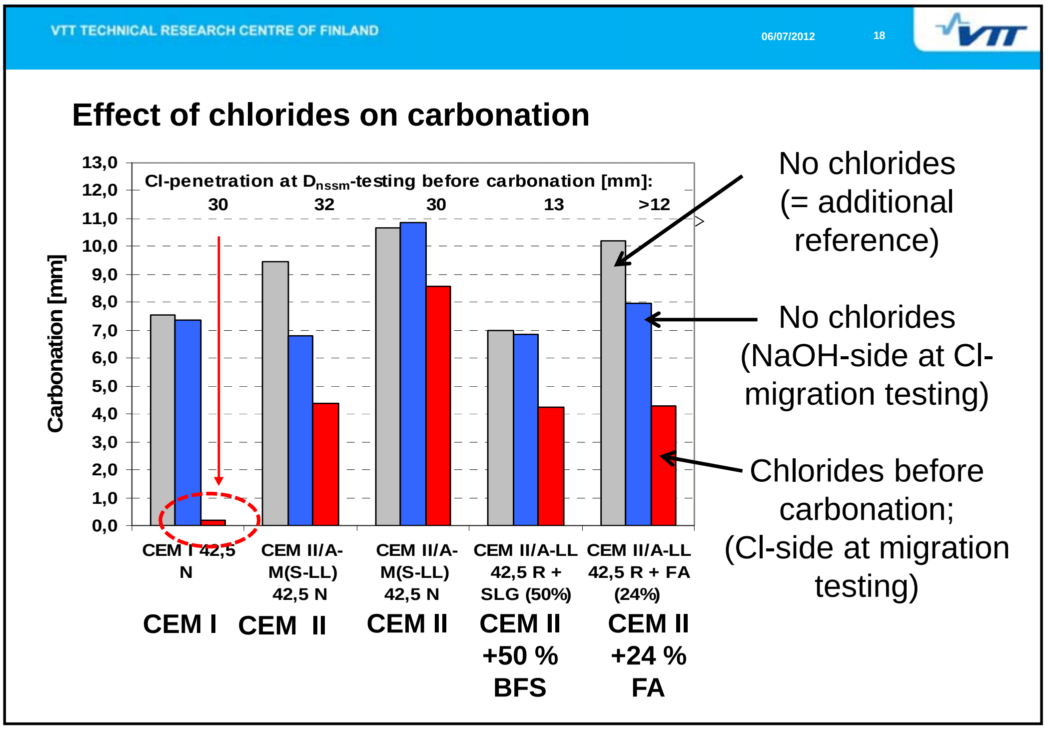
(DuraInt-project – Laboratory test results)

2. Effect of chlorides on carbonation - effect of FA/BFS

Mixes (concrete) – the same as in testing no. 1

Short code	Cement type	Weff/(Cement +0,80×BFS +0,40×FA)	Binder materials [kg/m³]			Total effective water [kg/m³]	Aggre-gates	Air content (fresh concrete) [%]	Compressive strength [MPa]	
			Cement	BFS	FA		Total [kg/m³]		7d	28d
Y05A2	CEM II/A-M(S-LL) 42.5 N	0,51	333	0	0	170	1899	1,4	42,8	57,4
Y05A5	CEM II/A-M(S-LL) 42.5 N	0,51	333	0	0	170	1844	4,4	36,9	50,8
R-BFS05A2	CEM II/A-LL 42.5 R & 50% Blast Furnace Slag	0,50	240	120	0	168	1888	2,2	43,5	66,8
R-FA05A2	CEM II/A-LL 42.5 R & 24% Fly Ash	0,50	300	0	72	165	1885	2,5	47,1	64,9
SR05A2	CEM I 42.5 N	0,50	321	0	0	160	1965	2,0	45,8	62,7


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
06/07/2012
17
VTT
Effect of chlorides on carbonation
First chloride penetration by NT Build 492 (age 3 months)
6.7 months
Carbonation: first at RH 65 %, and 56 d at 4 % CO_2 (RH 60 %)
1) Cl-side and
2) NaOH-side
Additional reference (separate specimens): Carbonation first at RH 65 %, and 56 d at 4 % CO_2 (RH 60 %)
4.7 months
50 mm
2) NaOH-side
1) Cl-side
Chloride penetration
Carbonatin


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
06/07/2012
18
VTT
Effect of chlorides on carbonation
Carbonation [mm]
Cl-penetration at D_{nssm}-testing before carbonation [mm]:
30
32
30
13
>12
13,0
12,0
11,0
10,0
9,0
8,0
7,0
6,0
5,0
4,0
3,0
2,0
1,0
0,0
CEM I 42,5 N
CEM II/A-M(S-LL) 42,5 N
CEM II/A-M(S-LL) 42,5 N
CEM II/A-LL 42,5 R + SLG (50%)
CEM II/A-LL 42,5 R + FA (24%)
CEM I
CEM II
CEM II
CEM II +50 % BFS
CEM II +24 % FA
No chlorides (= additional reference)
No chlorides (NaOH-side at Cl-migration testing)
Chlorides before carbonation; (Cl-side at migration testing)

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Effect of chlorides on carbonation

- Chlorides in concrete degreased carbonation
- Carbonation with chlorides was 3 % - 80 % of the carbonation without chlorides
- No big differences between the concretes with
  - CEM II/A-M(S-LL) 42,5, and
  - with CEM II/A-LL 42,5 R +**50 % BFS** or +**24 % FA**
- With **CEM I** 42,5 N carbonation was minimal with chlorides
  - Concrete with CEM I 42.5 N (SR-cement) has low chloride binding capacity
  - Higher concrete moisture content/RH and water film thickness inside the pores
  - Pores may become blocked as a result of the salt crystallization in the pores network
  -
  -

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Summary

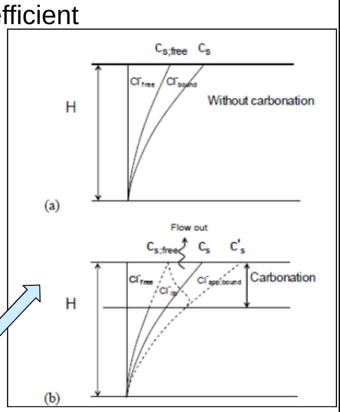
Carbonation >>> increase of chloride penetration
- relative increase was more with +FA/+BFS
- but with +FA/+BFS always lower migration coefficient

but

Chlorides >>> degrease of carbonation
- with CEM I (SR) significant degrease
- with CEM II no big effect of +FA/+BFS

and

Effects of liberation of bound chlorides
due to carbonation
without and with +FA/+BFS
- no test results yet
- modelling aspects (see DuraInt Task 5 – Service life)



VTT creates business from technology

Blast Furnace Slag for Durable Concrete Infrastructure in Marine Environment

Odd E. Gjørv

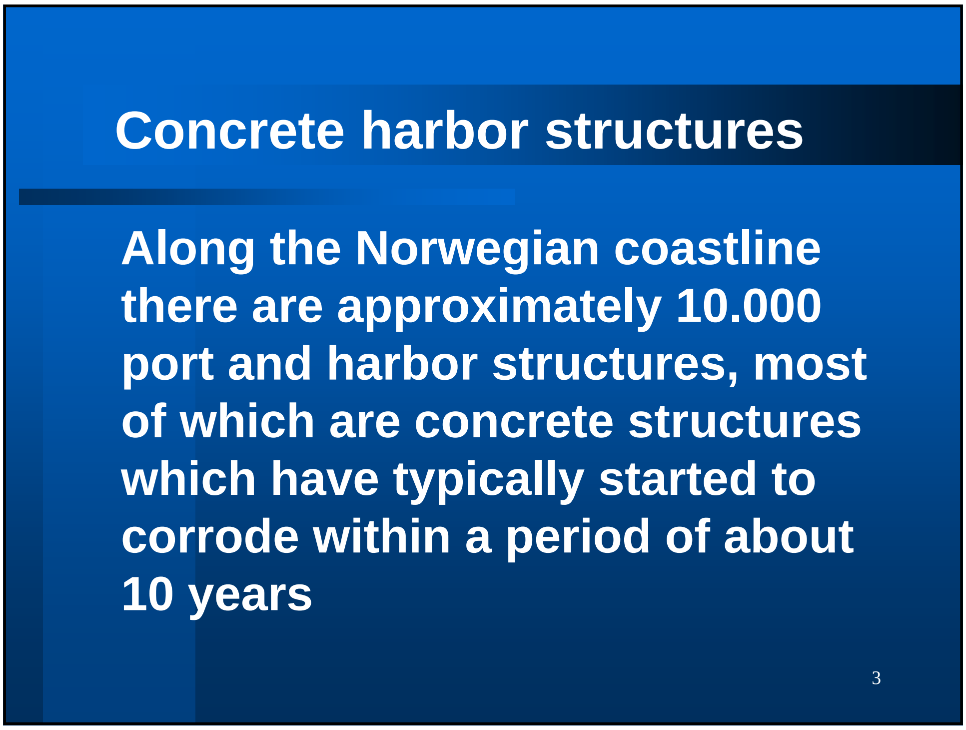
NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY - NTNU
Faculty of Engineering Science and Technology
Department of Structural Engineering, Trondheim, Norway

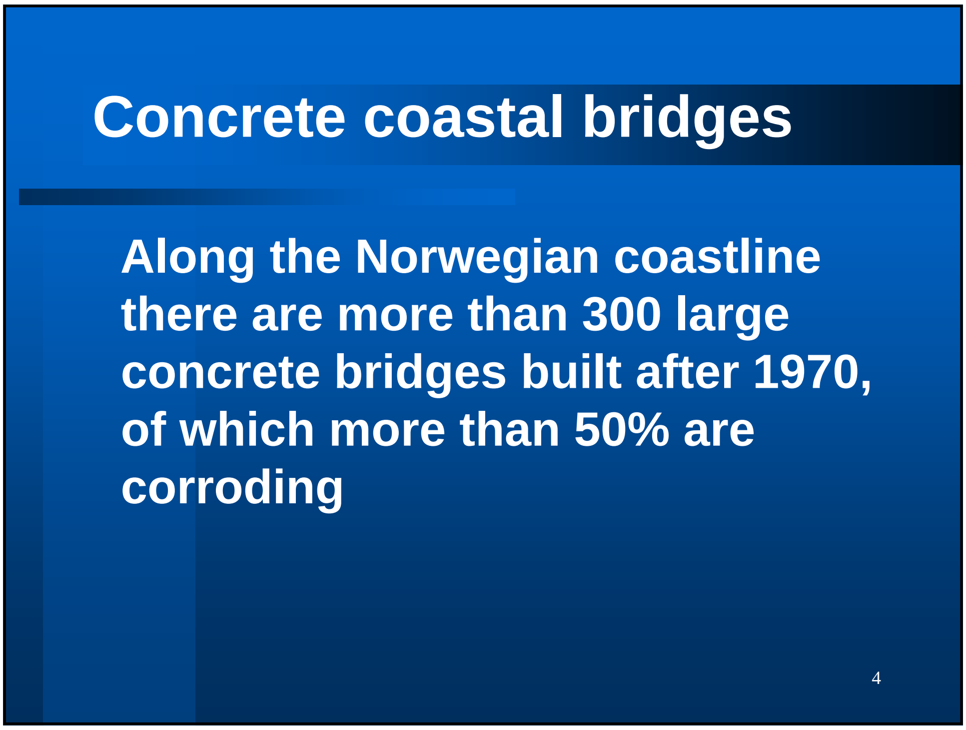
1

Field experience

- Along the Norwegian coastline there are a large number of important concrete structures exposed to a severe marine environment
- For all these concrete structures, chloride-induced corrosion represents the most serious problem and threat to the operation and safety of the structures

2


Concrete harbor structures
Along the Norwegian coastline there are approximately 10.000 port and harbor structures, most of which are concrete structures which have typically started to corrode within a period of about 10 years
3


Concrete coastal bridges
Along the Norwegian coastline there are more than 300 large concrete bridges built after 1970, of which more than 50% are corroding
4

Offshore concrete platforms

In the North Sea, 34 concrete platforms have been produced with high-performance concrete and very good durability. However, still corrosion of embedded steel has caused some very expensive repairs

5

Norwegian marine concrete construction

- The concrete has typically been produced with pure portland cements, and more recently also with fly ash cements
- All year concrete construction (low curing temperatures during winter)
- High risk for early-age exposure

6

Blast furnace slag cements (GGBS)

Since the first slag cements were introduced on the market (1888), extensive field experience and research in many countries have shown that such cements give a much higher resistance against chloride penetration than other cements

7

Blast furnace slag cements (GGBS) (cont.)

In order to also get some experience with slag cements in Norwegian marine environments, some experimental work was carried out

8

Objective

- Resistance against chloride penetration
  - General resistance
  - Early-age resistance
  - Effect of low curing temperature
- Frost resistance

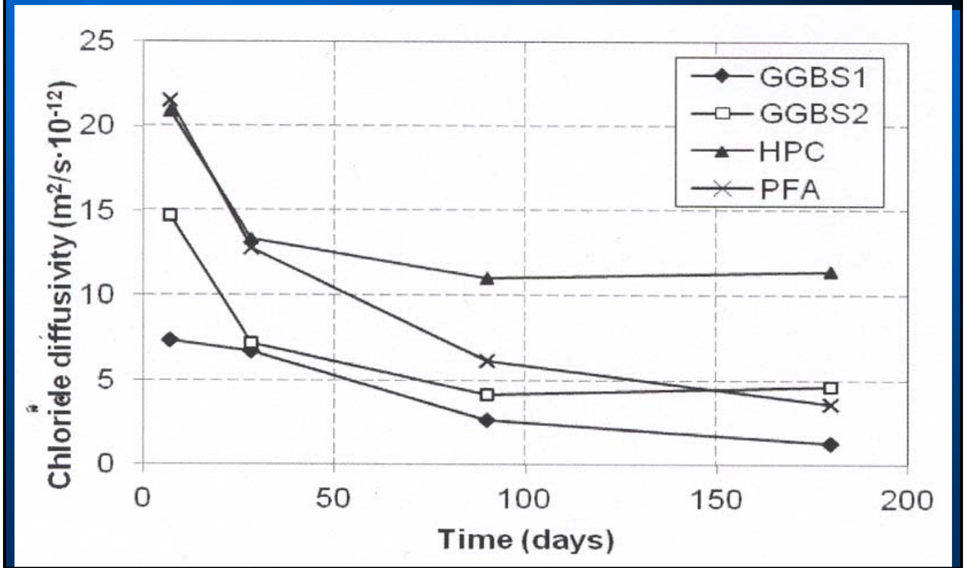
9

Chloride diffusivity (RCM)

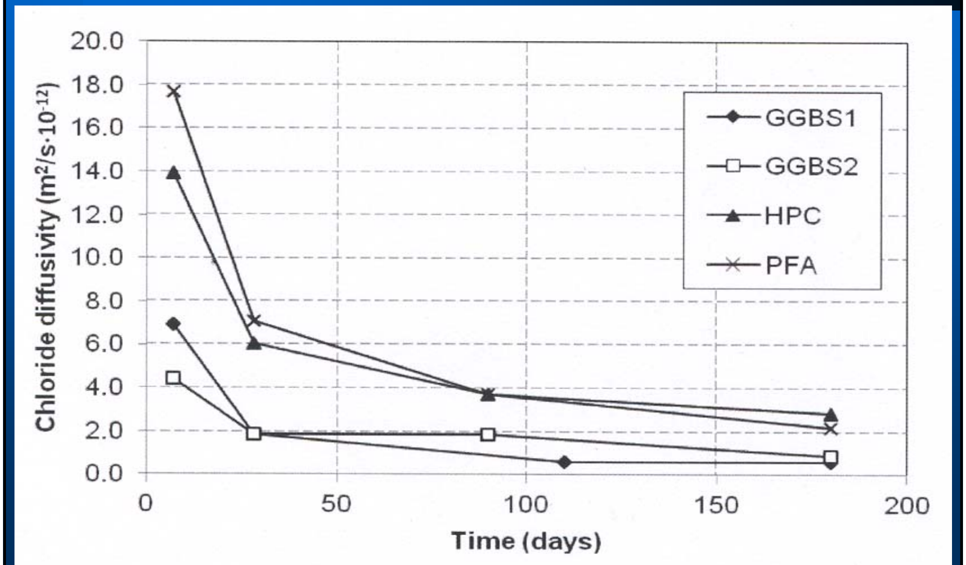
- Binder systems: GGBS 1 (34%), GGBS 2 (70%), HPC, OPC, PFA (20%)
- Curing temperatures: 5, 12, 20 ^{0}C
- Early-age resistance

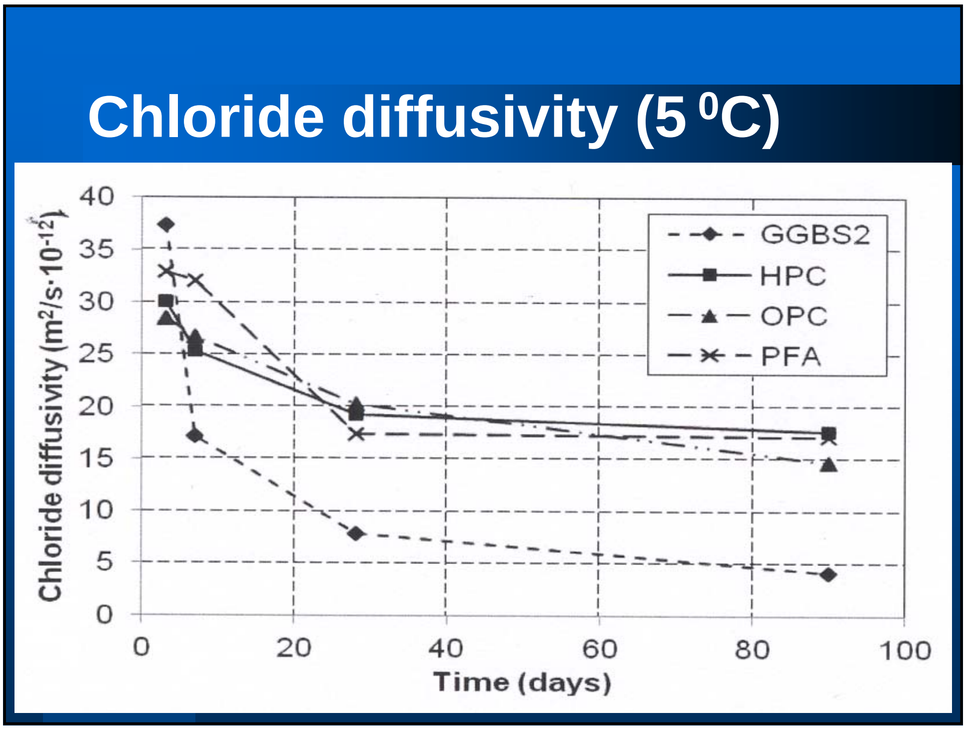
10

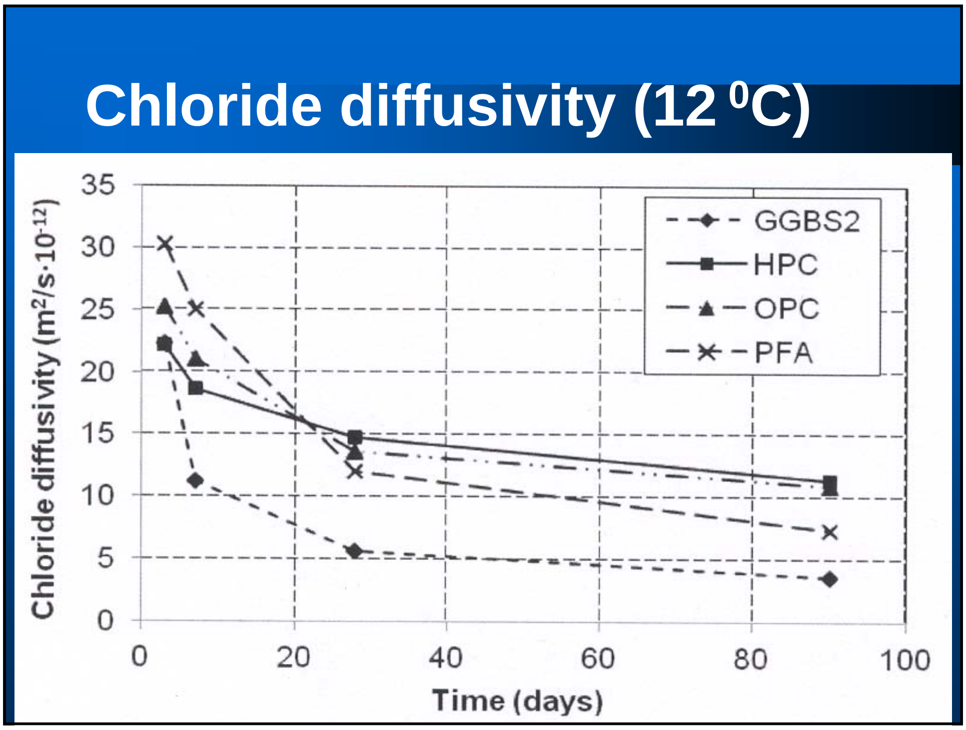
Chloride diffusivity (w/b = 0.45)



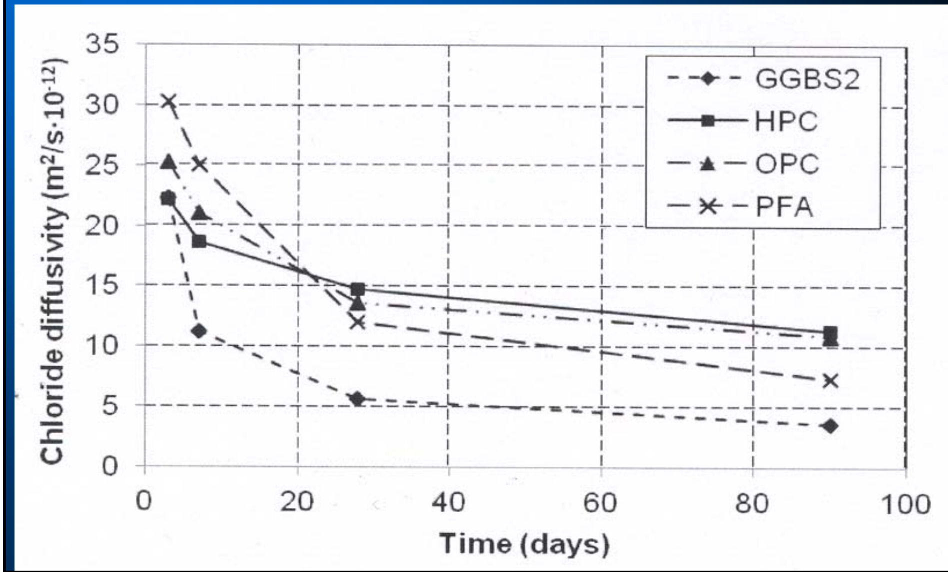
Chloride diffusivity (w/b = 0.38)




Chloride diffusivity (5 ⁰C)
Chloride diffusivity (m²/s·10⁻¹²)
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100
Time (days)
GGBS2
HPC
OPC
PFA


Chloride diffusivity (12 ⁰C)
Chloride diffusivity (m²/s·10⁻¹²)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
Time (days)
GGBS2
HPC
OPC
PFA

Chloride diffusivity (20 ^{0}C)



Freezing and thawing

- Three types of concrete with w/b = 0.37 (390 kg CEM III/B 42.5 + 39 kg CSF) and air void contents of 3 and 6% (0 %)
- Test methods
  - prEN 12390-9 (CDF) (TNO: 28 cycles)
  - SS 13 72 44 (SP: 112 cycles)

16

Freezing and thawing (cont.)

Both test methods showed that all three versions of the concrete with 70% slag cement had a good frost resistance regardless of varying air void content

17

Conclusion

The above results indicate that binder systems based on blast furnace slag should give superior durability in a typical Norwegian marine environment compared to that of other types of binder system

18

Statens vegvesen
Norwegian Public Roads Administration

The effect of fly ash and slag on critical parameters for rebar corrosion – NPRA experience

Claus K. Larsen, NPRA
Chief engineer, PhD

vegvesen.no

Motivation

In service:
- o more than 10 000 concrete bridges
- o nearly 1000 tunnels
- o many ferry quays

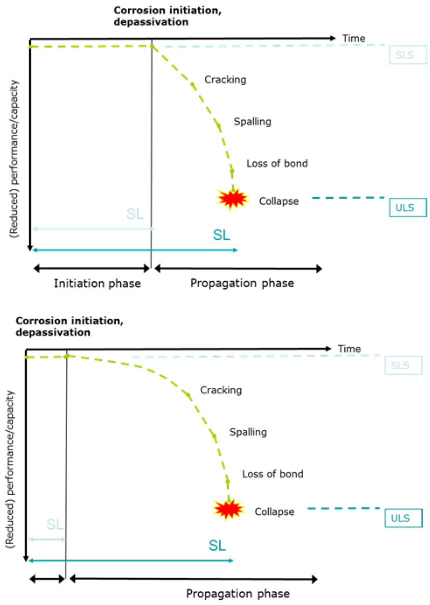
Building of new bridges with required Service Life of 100 years:
- o partial extreme exposure
- o long and complex structures

With a capital value of bridges of 50 billion NOK and 100 years life span, each extended year of lifetime can bring an economic saving of 500 million NOK.

Reliable prediction and assessment for existing structures together with choosing proper materials and design becomes important.

vegvesen.no

Statens vegvesen
Norwegian Public Roads Administration



The initiation phase is controlled by

- o Cover depth
- o Diffusion of chlorides (concrete quality)

Depassivation is controlled by

- o [Cl^-]
- o pH
- o E_{steel}

$\left.\begin{matrix} [Cl^-] \\ pH \\ E_{steel} \end{matrix}\right\} C_{crit}$

The propagation phase is controlled by

- o Corrosion rate
- o (Structural properties)

Key «material» parameters

D_{Cl}	C_{crit}	i_{corr}

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Critical parameters for corrosion

FA and slag generally decreases chloride diffusion rates

Time effects?

Key «material» parameters

D_{Cl}	C_{crit}	i_{corr}

?

FA and slag generally increases the electrical resistivity of concrete

Increased resistivity decreases corrosion rates?

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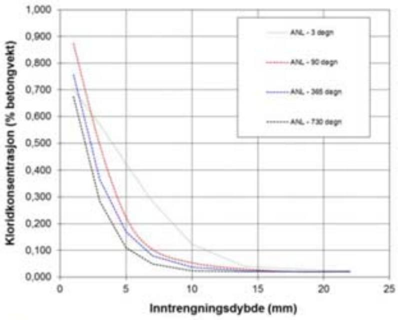
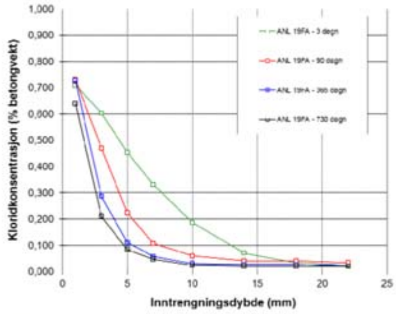
Effects of time to (age at) chloride exposure



ANL



ANL-19FA

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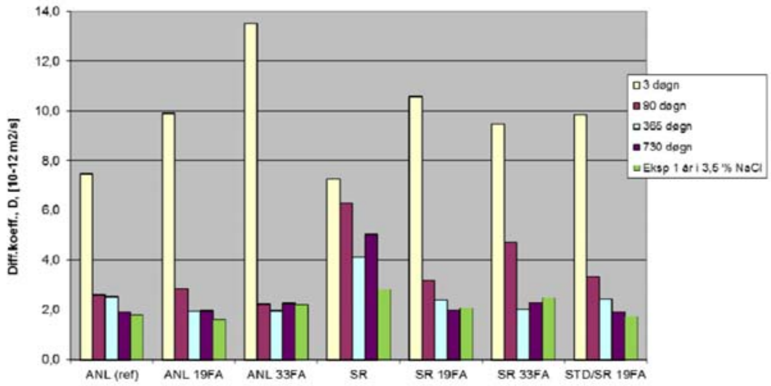
Effects of time to (age at) chloride exposure



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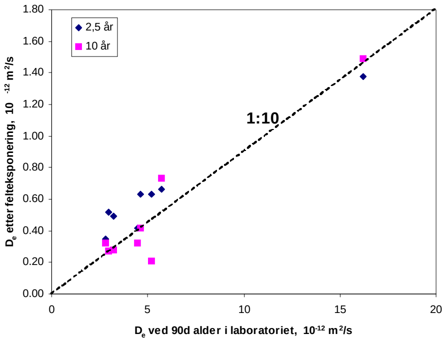
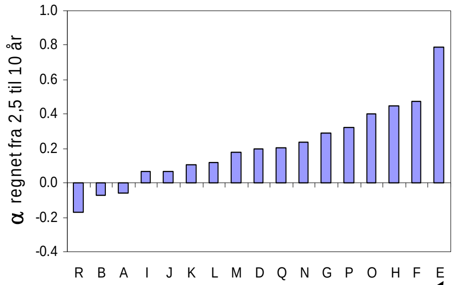
D_{Cl} changes with time due to "ageing effect"

$$\frac{D_t}{D_0} = \left(\frac{t_0}{t}\right)^{\alpha}$$

17 different concretes exposed in Northern Norway

Change from 2.5 to 10 years





20% FA

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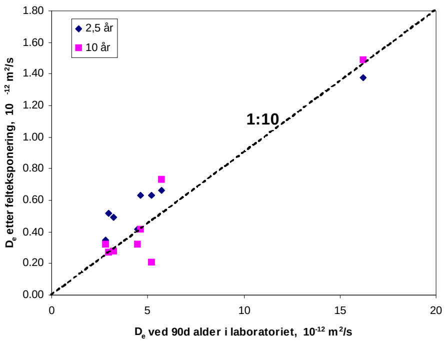
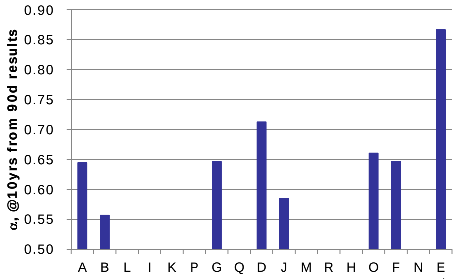
D_{Cl} changes with time due to "ageing effect"

$$\frac{D_t}{D_0} = \left(\frac{t_0}{t}\right)^{\alpha}$$

17 different concretes exposed in Northern Norway

Change from 2.5 to 10 years





20% FA

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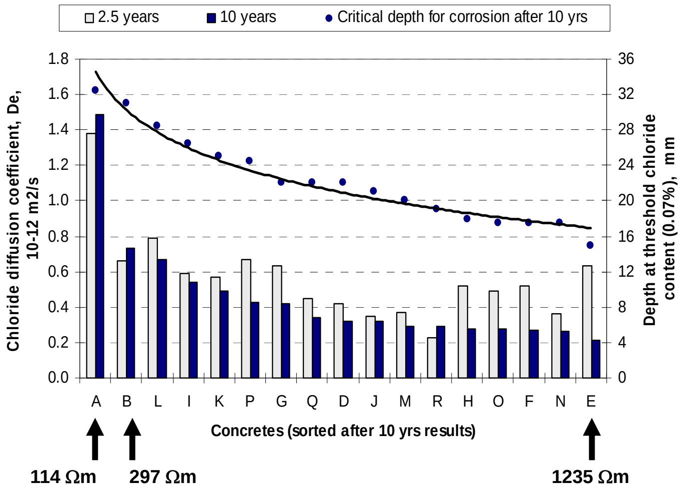
The importance of resistivity



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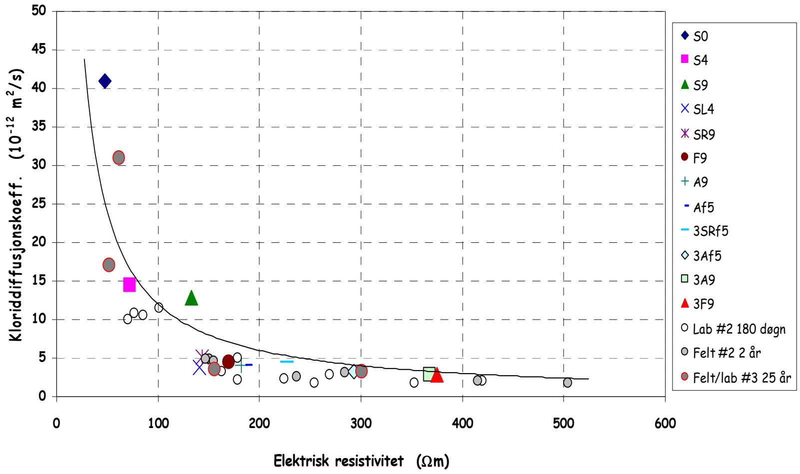
The importance of resistivity - D_{Cl}



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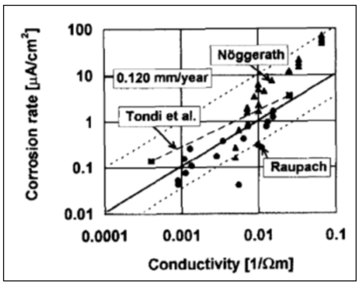
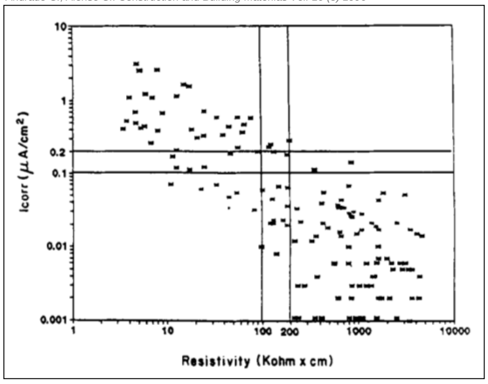
The importance of resistivity - i_{corr}



Hunkeler F. : Construction and Building Materials Vol. 10 (5) 1996

Andrade C.; Alonso C.: Construction and Building Materilas Vol. 10 (5) 1996



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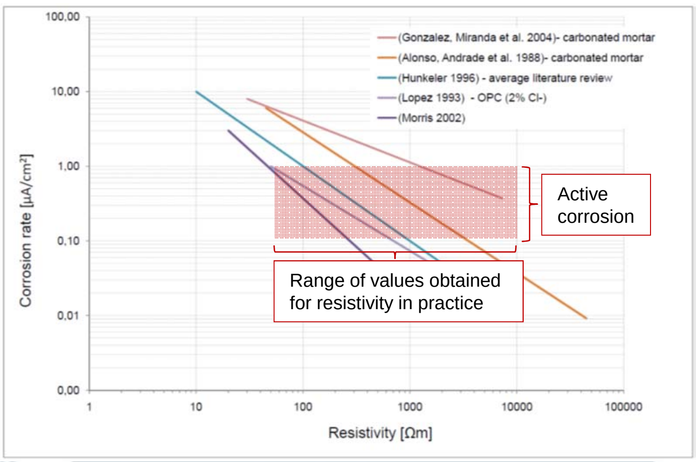
The importance of resistivity - i_{corr}



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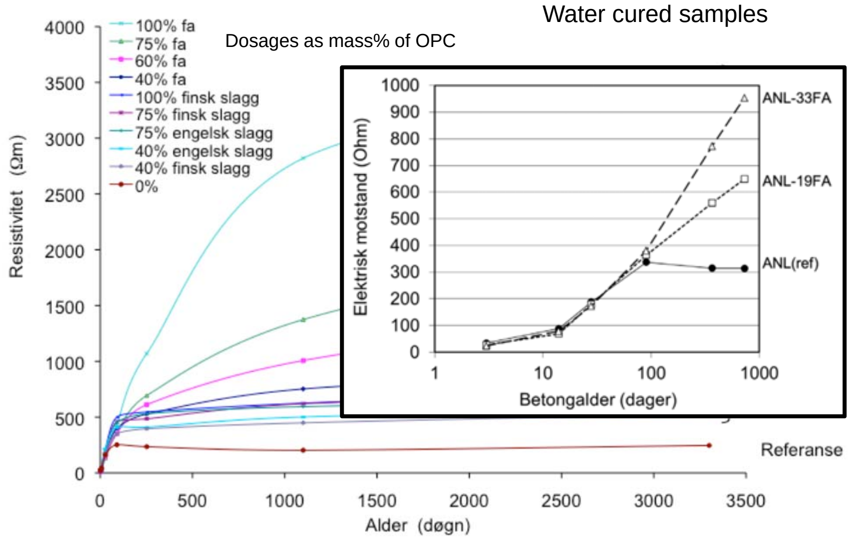
The influence of FA and slag on resistivity



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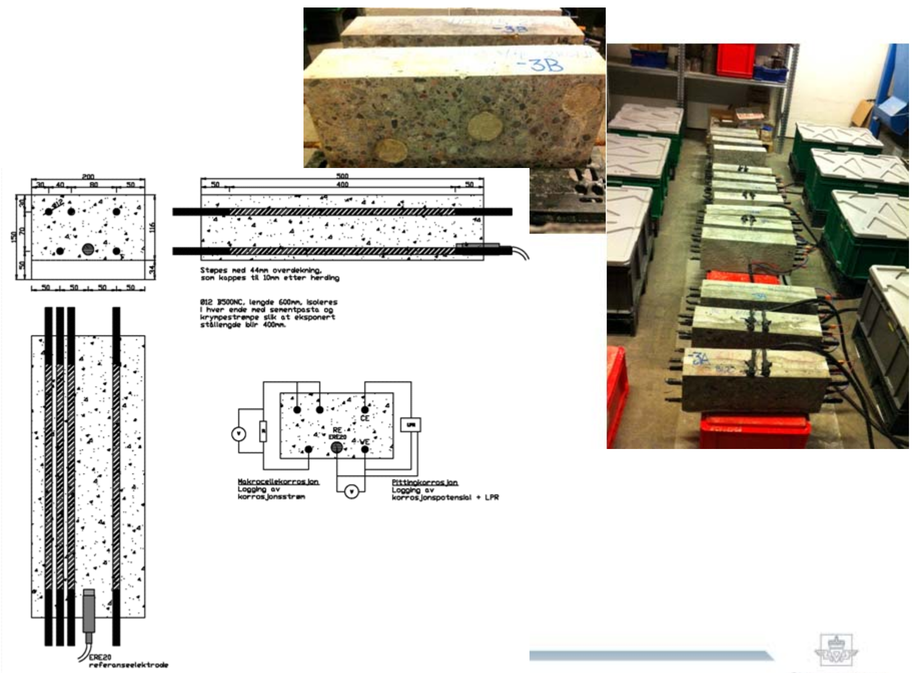

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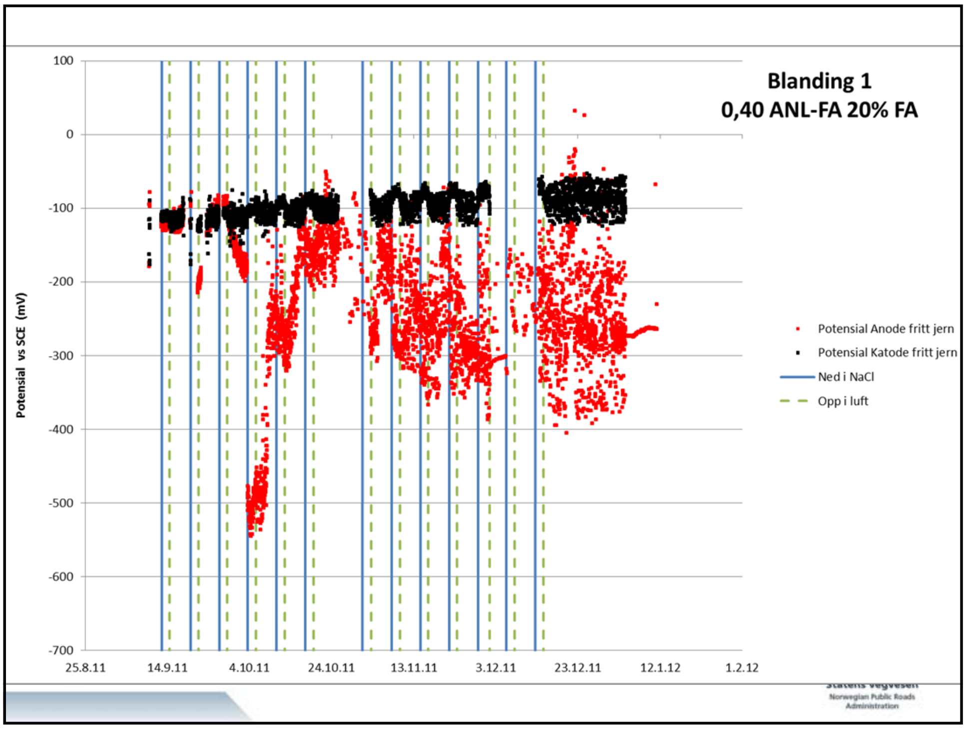
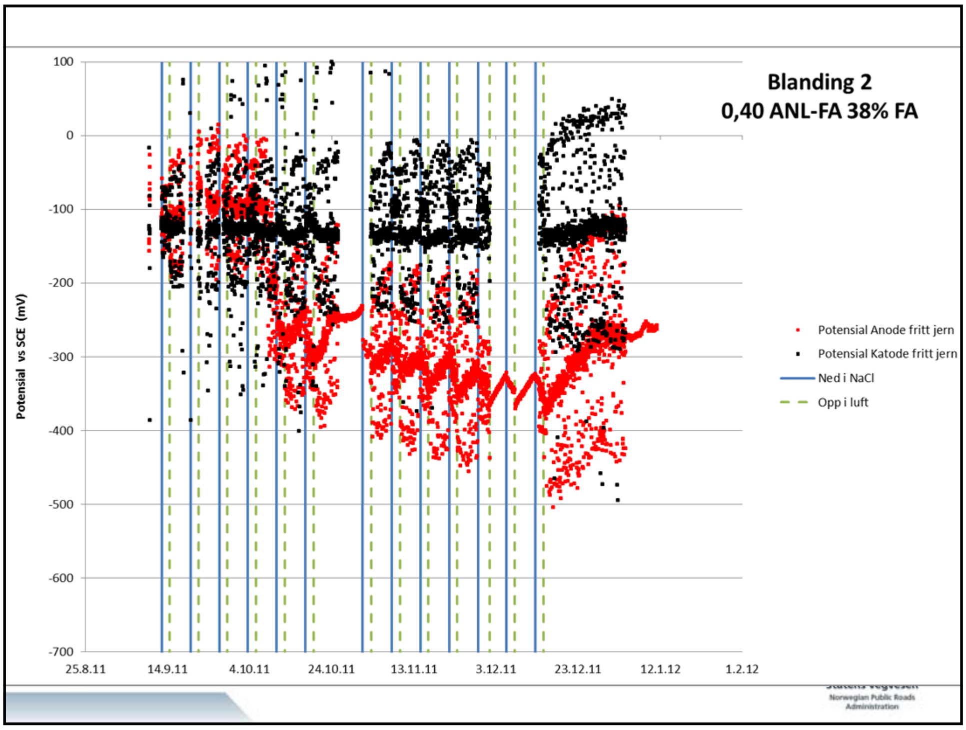
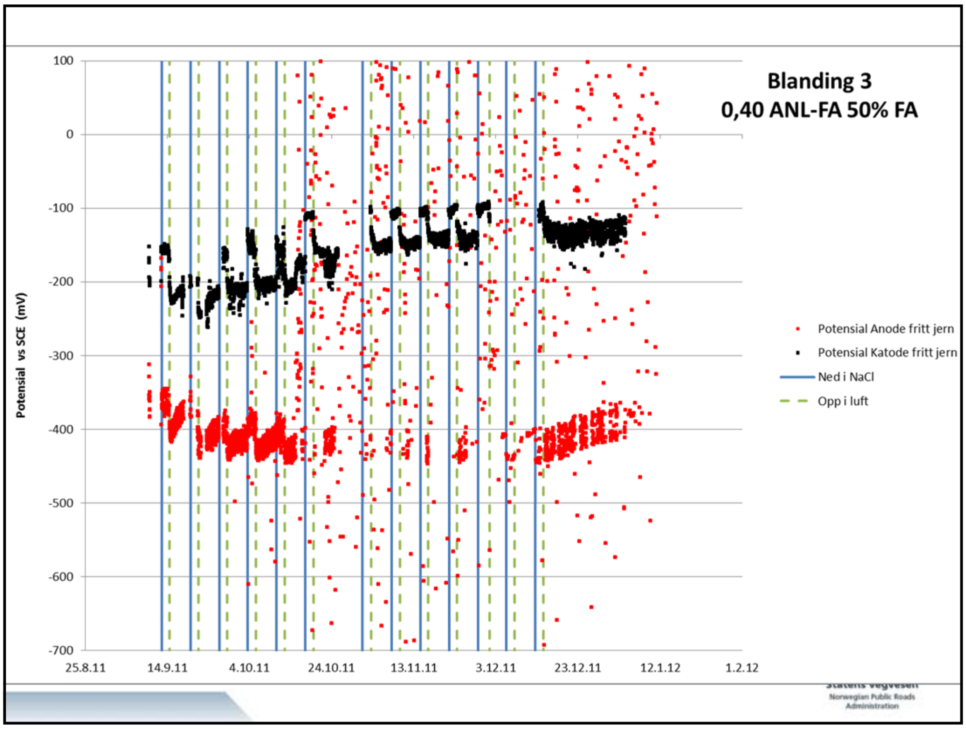
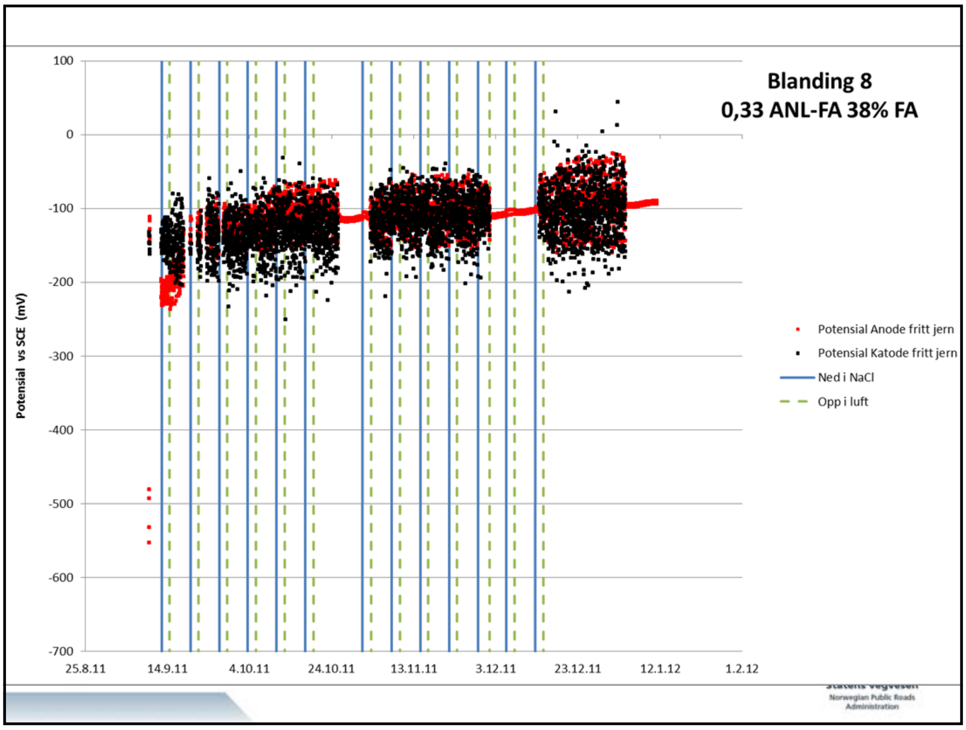
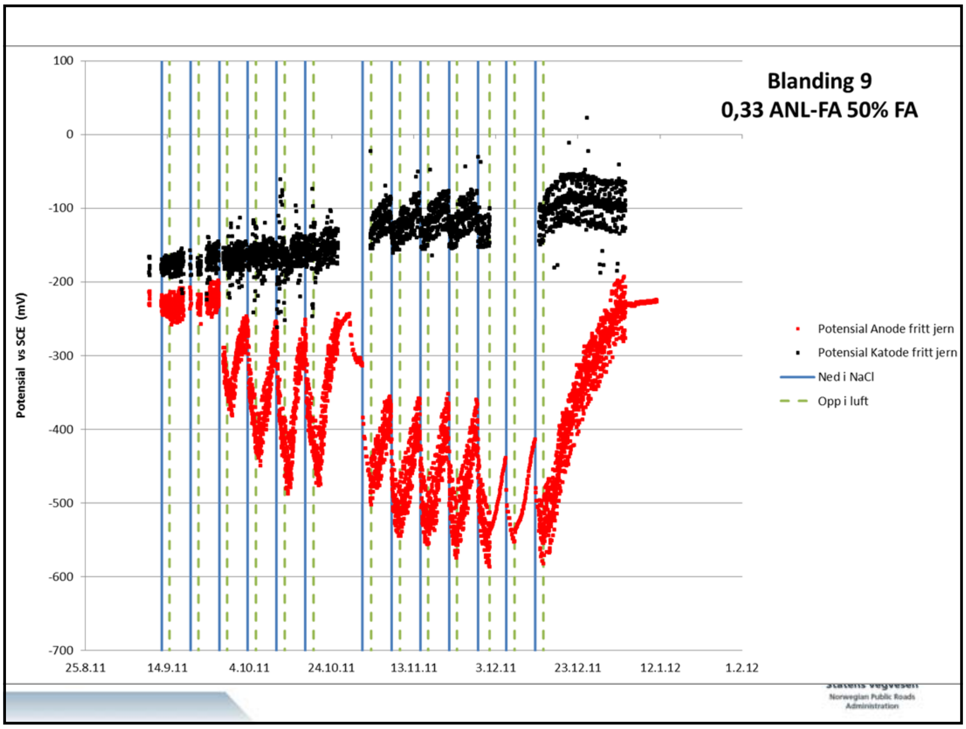
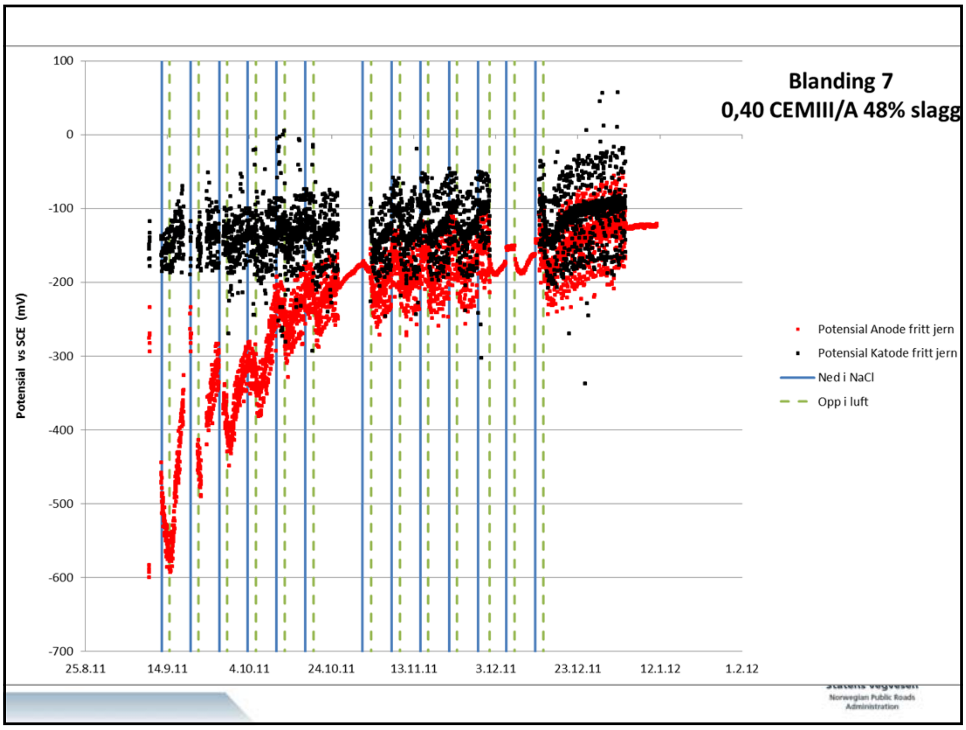

Blanding 1
0,40 ANL-FA 20% FA
Potensial vs SCE (mV)
100
0
-100
-200
-300
-400
-500
-600
-700
25.8.11
14.9.11
4.10.11
24.10.11
13.11.11
3.12.11
23.12.11
12.1.12
1.2.12
Potensial Anode fritt jern
Potensial Katode fritt jern
Ned i NaCl
Opp i luft
Norwegian Public Roads Administration

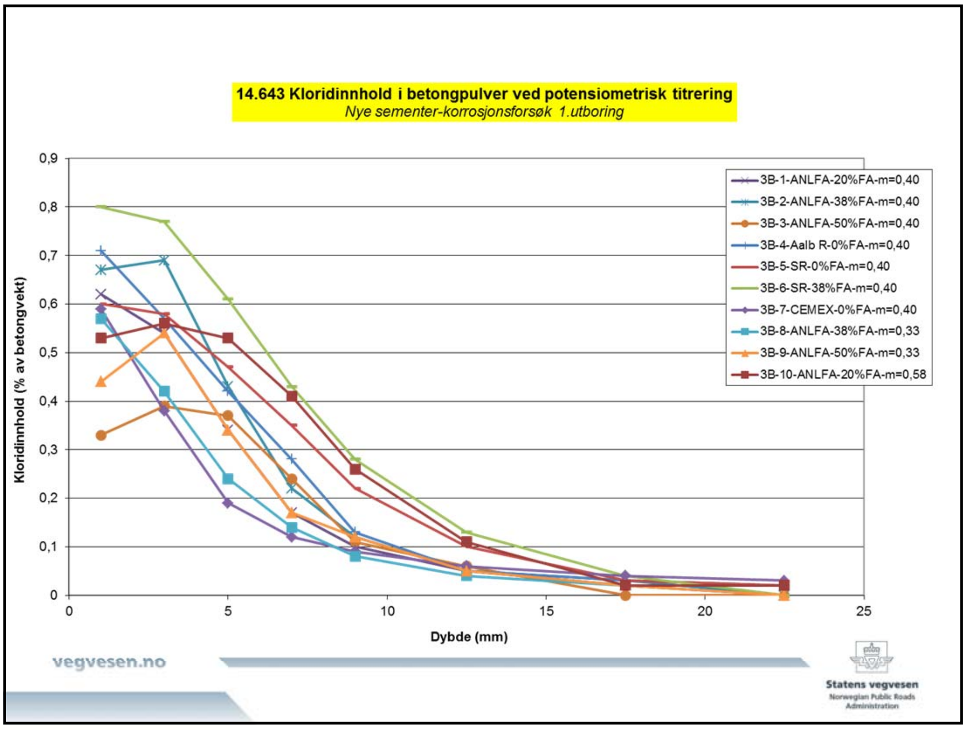

Blanding 2
0,40 ANL-FA 38% FA
Potensial vs SCE (mV)
100
0
-100
-200
-300
-400
-500
-600
-700
25.8.11
14.9.11
4.10.11
24.10.11
13.11.11
3.12.11
23.12.11
12.1.12
1.2.12
Potensial Anode fritt jern
Potensial Katode fritt jern
Ned i NaCl
Opp i luft
Norwegian Public Roads Administration


Blanding 3
0,40 ANL-FA 50% FA
Potensial vs SCE (mV)
100
0
-100
-200
-300
-400
-500
-600
-700
25.8.11
14.9.11
4.10.11
24.10.11
13.11.11
3.12.11
23.12.11
12.1.12
1.2.12
Potensial Anode fritt jern
Potensial Katode fritt jern
Ned i NaCl
Opp i luft


Blanding 8
0,33 ANL-FA 38% FA
Potensial vs SCE (mV)
100
0
-100
-200
-300
-400
-500
-600
-700
25.8.11
14.9.11
4.10.11
24.10.11
13.11.11
3.12.11
23.12.11
12.1.12
1.2.12
Potensial Anode fritt jern
Potensial Katode fritt jern
Ned i NaCl
Opp i luft


Blanding 9
0,33 ANL-FA 50% FA
Potensial vs SCE (mV)
100
0
-100
-200
-300
-400
-500
-600
-700
25.8.11
14.9.11
4.10.11
24.10.11
13.11.11
3.12.11
23.12.11
12.1.12
1.2.12
Potensial Anode fritt jern
Potensial Katode fritt jern
Ned i NaCl
Opp i luft
Norwegian Public Roads Administration


Blanding 7
0,40 CEMIII/A 48% slagg
Potensial vs SCE (mV)
100
0
-100
-200
-300
-400
-500
-600
-700
25.8.11
14.9.11
4.10.11
24.10.11
13.11.11
3.12.11
23.12.11
12.1.12
1.2.12
Potensial Anode fritt jern
Potensial Katode fritt jern
Ned i NaCl
Opp i luft
Norwegian Public Roads Administration


14.643 Kloridinnhold i betongpulver ved potensiometrisk titrering
Nye sementer-korrosjonsforsøk 1.utboring
Kloridinnhold (% av betongvekt)
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
5
10
15
20
25
Dybde (mm)
3B-1-ANLFA-20%FA-m=0,40
3B-2-ANLFA-38%FA-m=0,40
3B-3-ANLFA-50%FA-m=0,40
3B-4-Aalb R-0%FA-m=0,40
3B-5-SR-0%FA-m=0,40
3B-6-SR-38%FA-m=0,40
3B-7-CEMEX-0%FA-m=0,40
3B-8-ANLFA-38%FA-m=0,33
3B-9-ANLFA-50%FA-m=0,33
3B-10-ANLFA-20%FA-m=0,58
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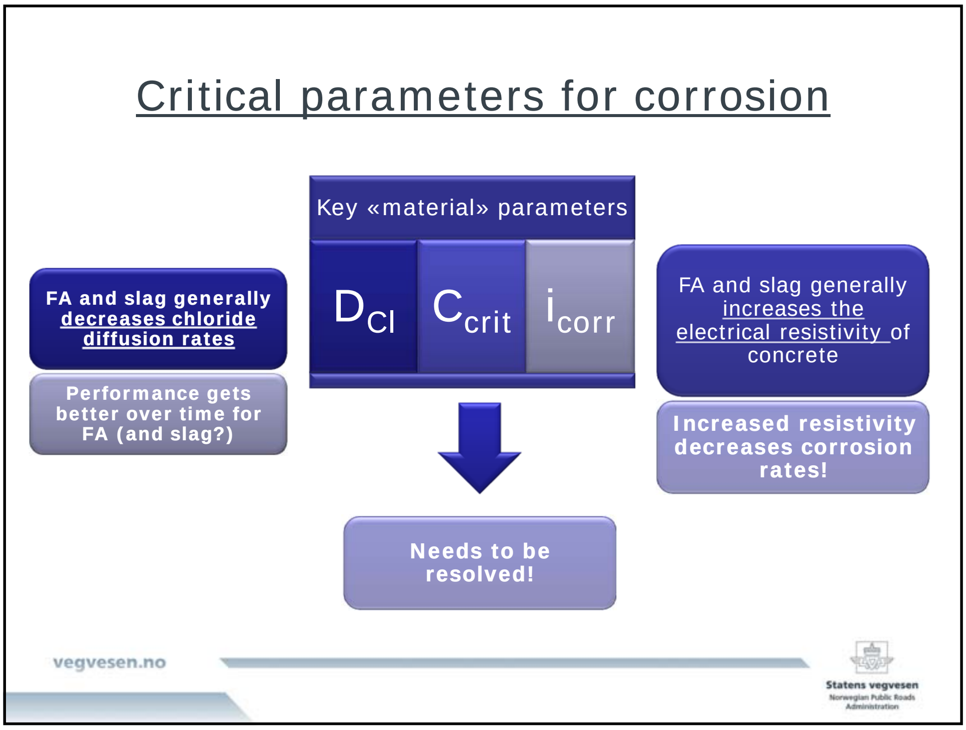
Critical parameters for corrosion
Key «material» parameters
D_{Cl}
C_{crit}
i_{corr}
FA and slag generally decreases chloride diffusion rates
Performance gets better over time for FA (and slag?)
FA and slag generally increases the electrical resistivity of concrete
Increased resistivity decreases corrosion rates!
Needs to be resolved!
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Frost Resistance of Concrete Containing Secondary Cementitious Materials

Experience from field and laboratory investigations

Peter Utgenannt
CBI - Swedish Cement and Concrete Research Institute

Swedish Cement and Concrete Research Institute

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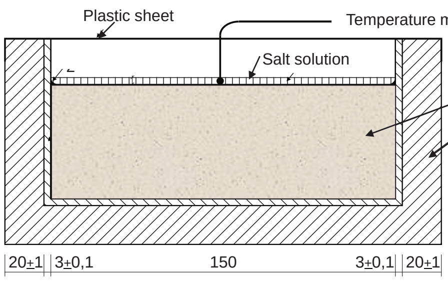
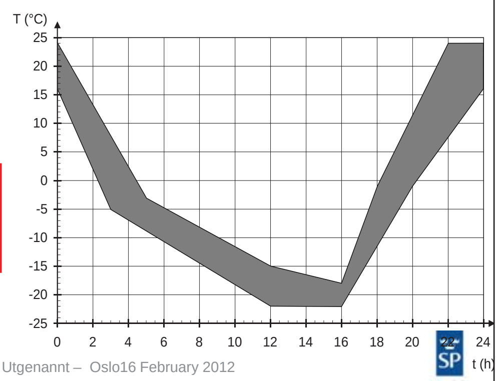
The SLAB METHOD for salt-frost scaling CEN/TS 12390-9



The specimen is dried (65% RH, 20 ºC) for 7 days before testing

The loss of mass/m² (scaling) is measured after 7, 14, 28, 42 and 56 cycles



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Background

- The test method for scaling resistance (SS 13 72 44, CEN TS 12390-9) was developed based on experience from concrete with CEM I, w/b-ratio 0,40-0,50 and with entrained air.
- Today this test method is used for evaluating the scaling resistance of many different types of concretes with different binder types, additions, low w/b-ratio etc
- CEN TS 12390-9 is now being revised within CEN/TC51/WG12/TG4

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Questions

- Is it possible to evaluate the scaling resistance of concrete with new cement types, additions and low w/b-ratio with the traditional scaling test (CEN/TS 12390-9)?
- How do ageing influence the scaling resistance of concrete produced with different cement types?
- Do we need to change the scaling test in order to better consider the possible ageing effects?

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- Field investigations to correlate results from the field with results from the laboratory.
- Laboratory investigations to study the effect of ageing on the scaling resistance.
- Conclusions and suggestions

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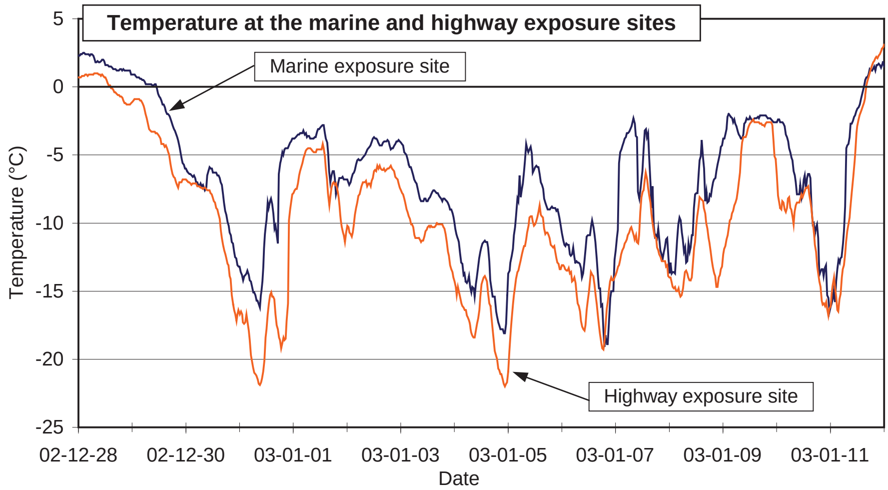

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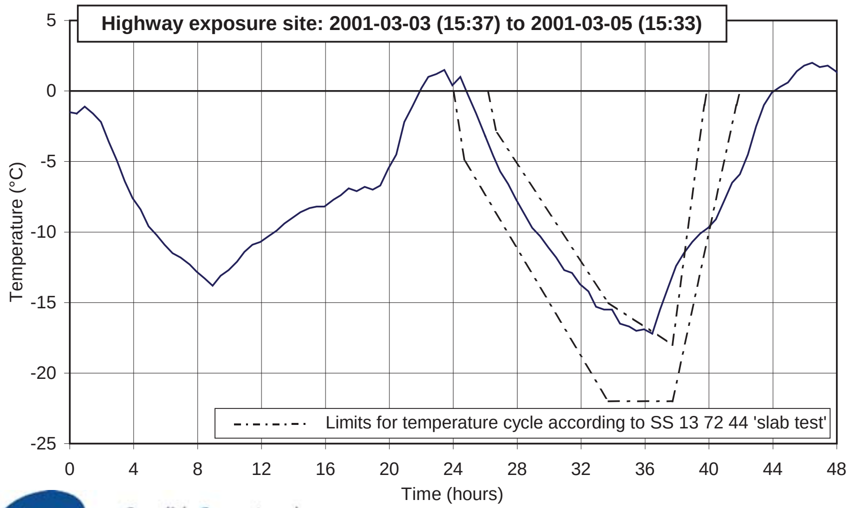
Freeze/thaw cycle in the field



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Concrete qualities 1996

Six different binder types

- CEM I
- CEM II/A-LL
- CEM II/A-S
- CEM I + 5% silica
- CEM I + 30% slag
- CEM III/B (~70% slag) (Dutch slag cement)

Two binder types placed at the test site 1997

- CEM II/A-V
- CEM II/A-V + 3,8% silica

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Concrete qualities

10 different concrete qualities per binder type

w/b 0.30 0.35 0.40 0.50 0.75
with entrained air ~4.5%
without entrained air 1-2%

CEM II/A-V w/b 0,40 and 0,42; ~4,5% air
CEM II/A-V +3,8% silica w/b 0,40; ~4,5 % air

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Measuring external and internal damage

- Volume change

- Ultrasonic pulse transmission time

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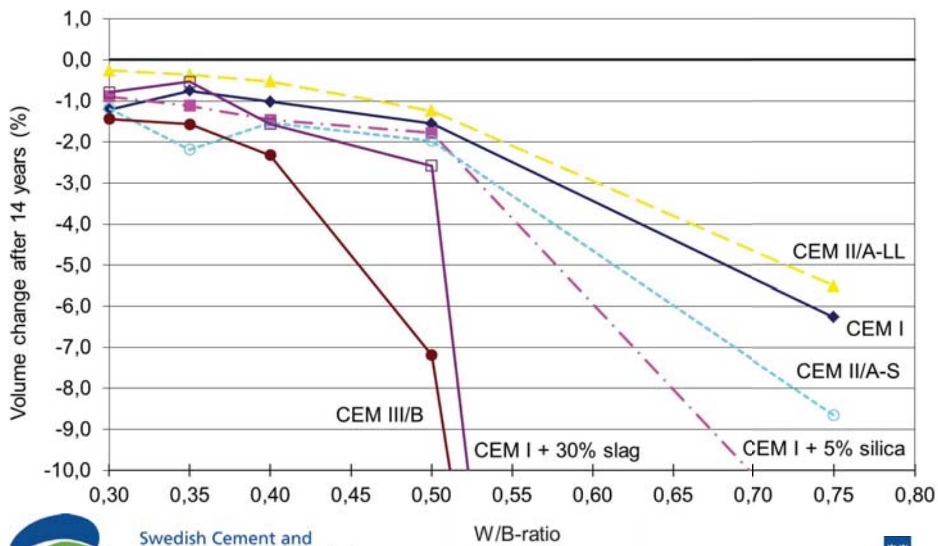
Highway environment – with entrained air



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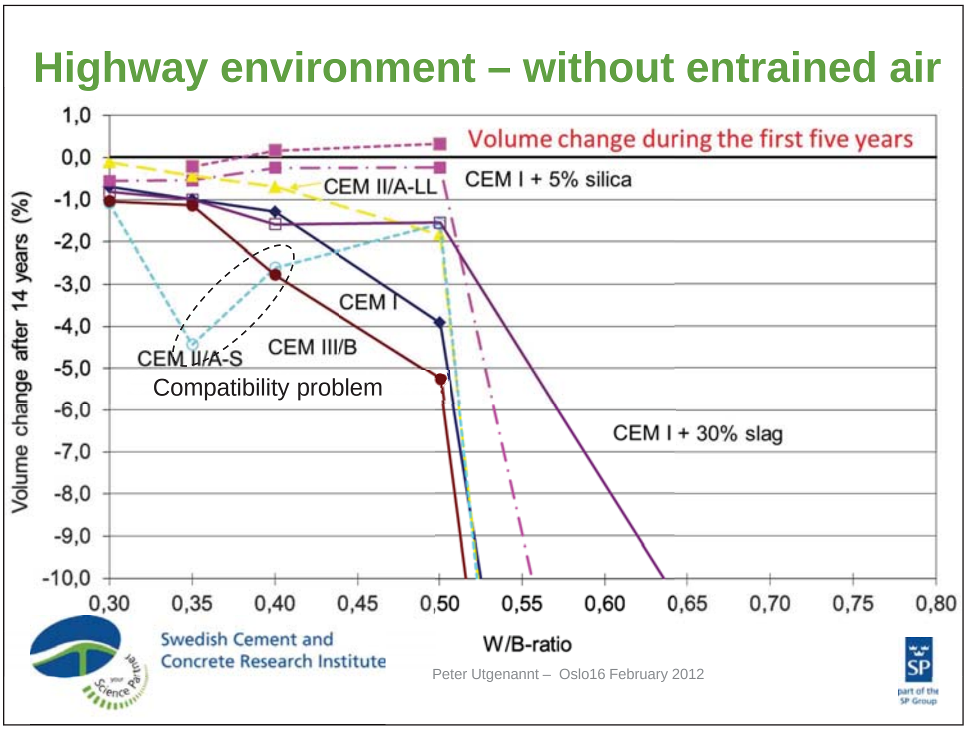
Highway environment – without entrained air
Volume change during the first five years
CEM II/A-LL
CEM I + 5% silica
CEM I
CEM II/A-S
CEM III/B
Compatibility problem
CEM I + 30% slag
Volume change after 14 years (%)
W/B-ratio
1,0
0,0
-1,0
-2,0
-3,0
-4,0
-5,0
-6,0
-7,0
-8,0
-9,0
-10,0
0,30
0,35
0,40
0,45
0,50
0,55
0,60
0,65
0,70
0,75
0,80
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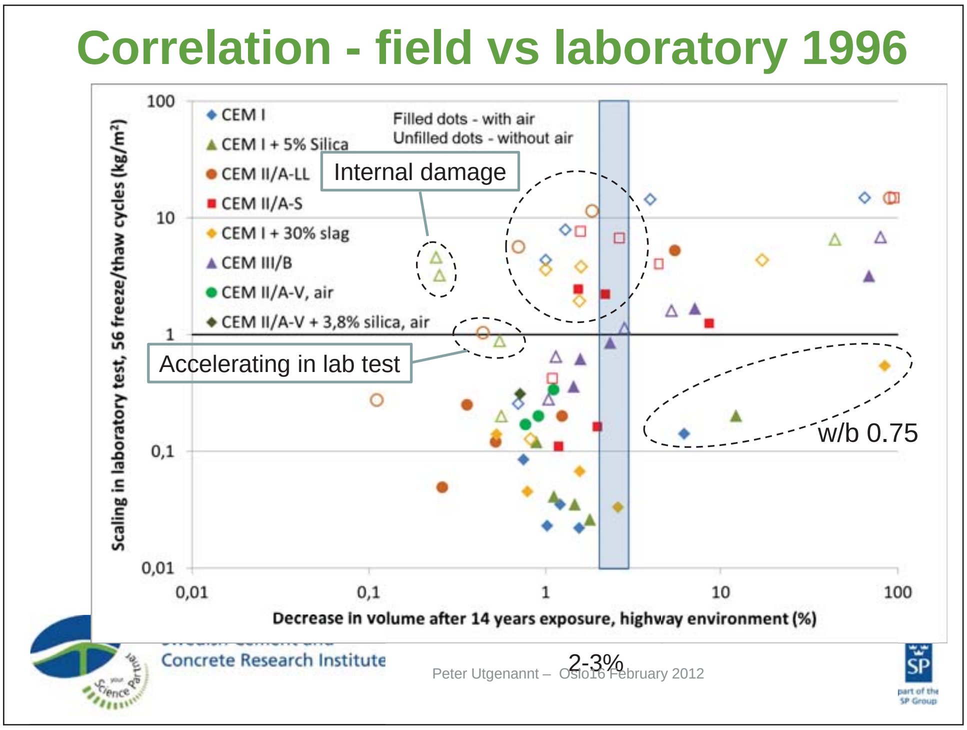
Correlation - field vs laboratory 1996
CEM I
CEM I + 5% Silica
CEM II/A-LL
CEM II/A-S
CEM I + 30% slag
CEM III/B
CEM II/A-V, air
CEM II/A-V + 3,8% silica, air
Filled dots - with air
Unfilled dots - without air
Internal damage
Accelerating in lab test
w/b 0.75
2-3%
Scaling in laboratory test, 56 freeze/thaw cycles (kg/m²)
Decrease in volume after 14 years exposure, highway environment (%)
100
10
1
0,1
0,01
0,01
0,1
1
10
100
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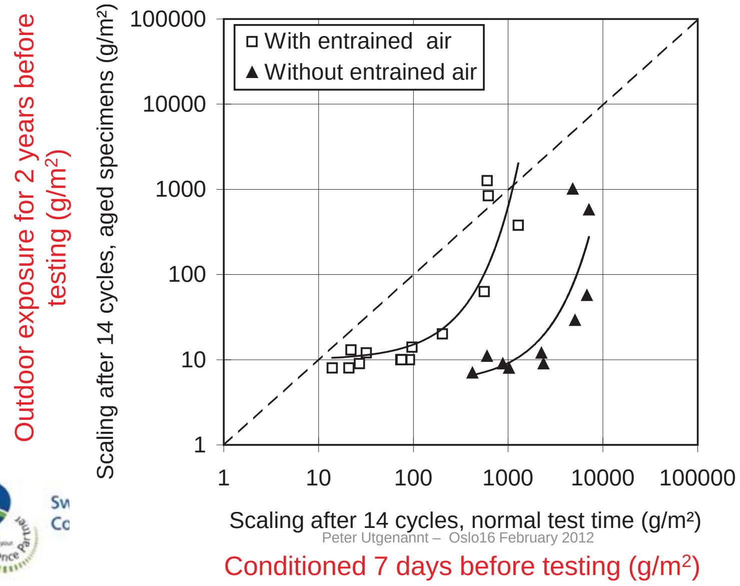
Testing of scaling resistance – laboratory versus specimens aged at the marine test site for two years



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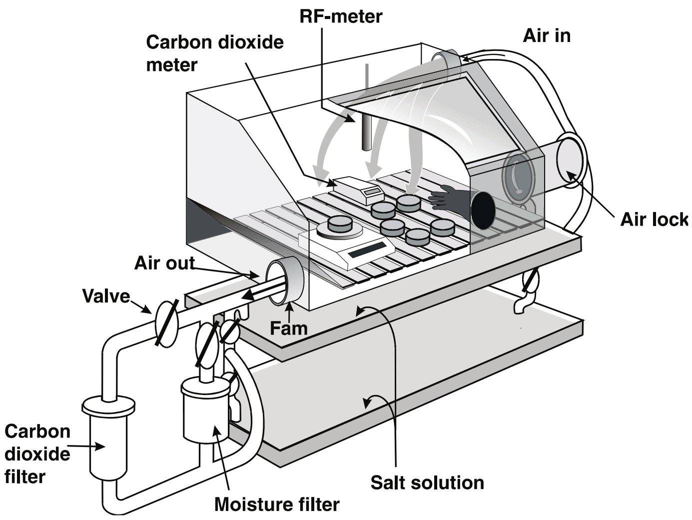
Laboratory investigation about the effect of ageing



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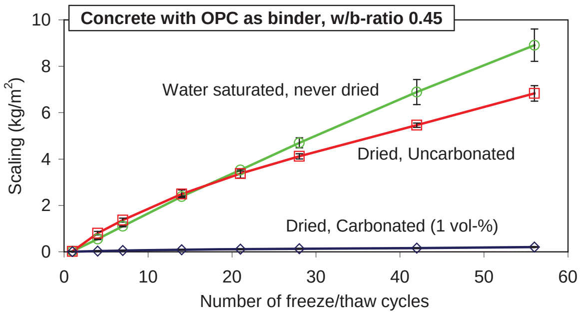
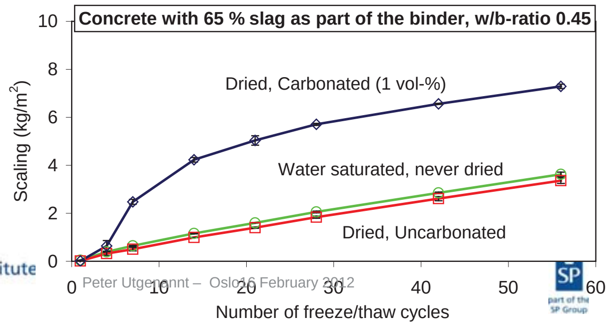
Effect of ageing on the salt-frost resistance



Dried = stored in 65% RH / 20C



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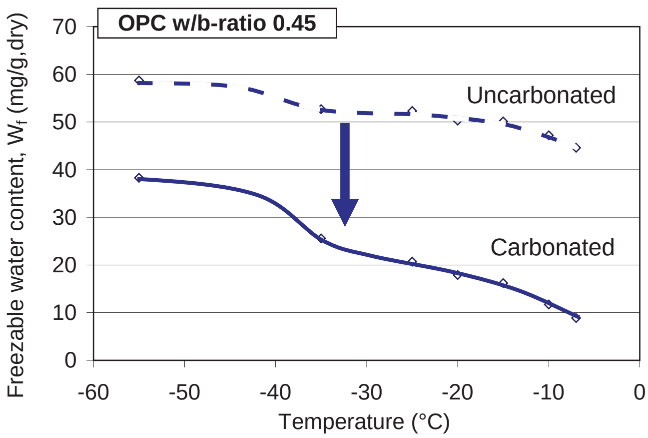
Freezable water content – CEM I



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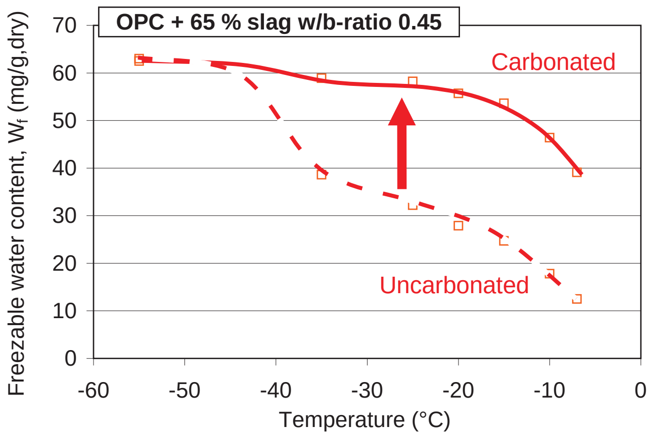
Freezable water content – CEM I + 65 % slag



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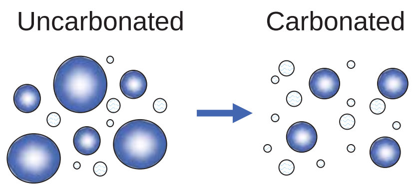
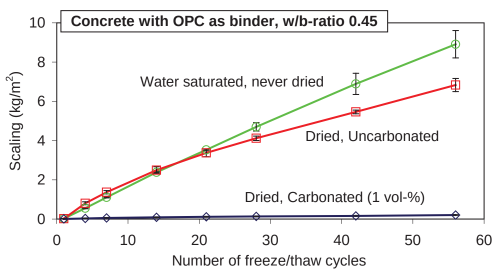
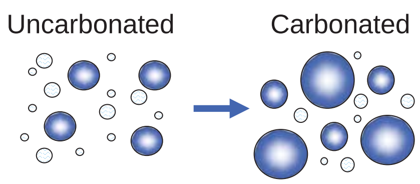
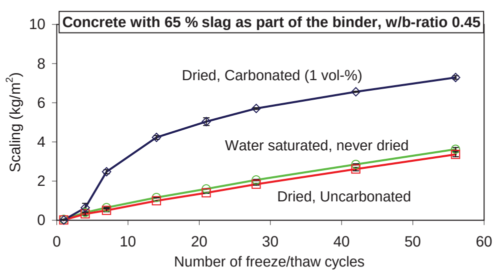
Concrete with CEM I





Concrete with CEM III





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Effect of the preconditioning time on the scaling results

Testing according to CEN/TS 12390-9 but with different conditioning periods (7, 14 and 21 days)

Cement types

- CEM I (SR LA MH)
- CEM II A-V (14% flyash, 5% limestone)
- CEM II B-M (S-LL) (18% slag, 8% limestone)

W/C-ratio 0,40

With 4,5% air

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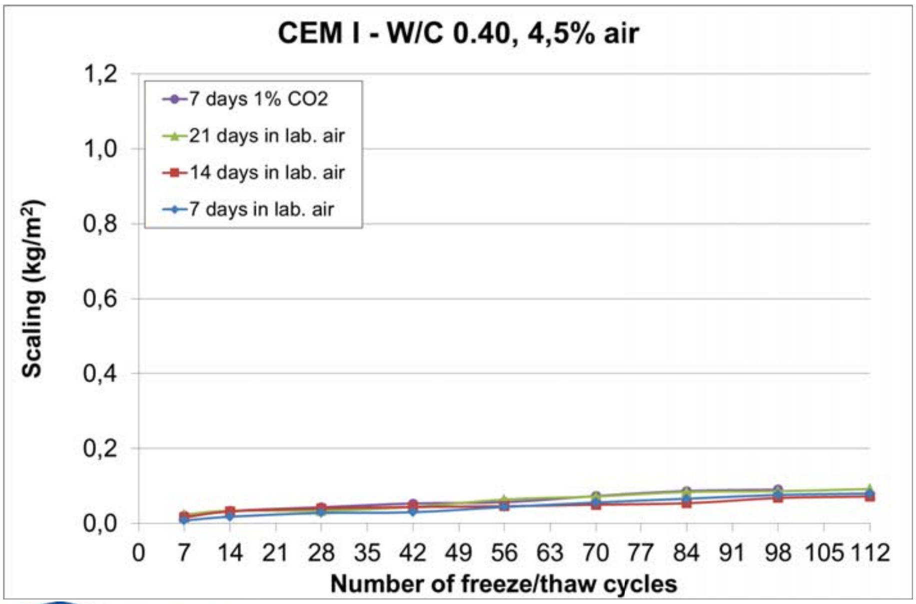

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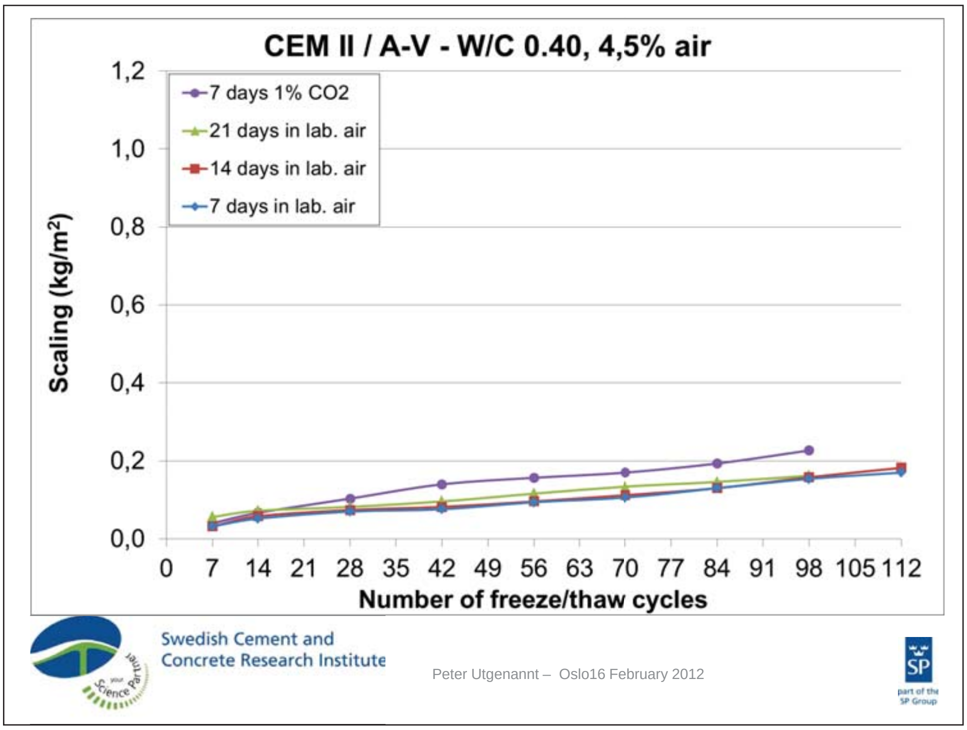
CEM II / A-V - W/C 0.40, 4,5% air
7 days 1% CO2
21 days in lab. air
14 days in lab. air
7 days in lab. air
Scaling (kg/m²)
1,2
1,0
0,8
0,6
0,4
0,2
0,0
0 7 14 21 28 35 42 49 56 63 70 77 84 91 98 105 112
Number of freeze/thaw cycles
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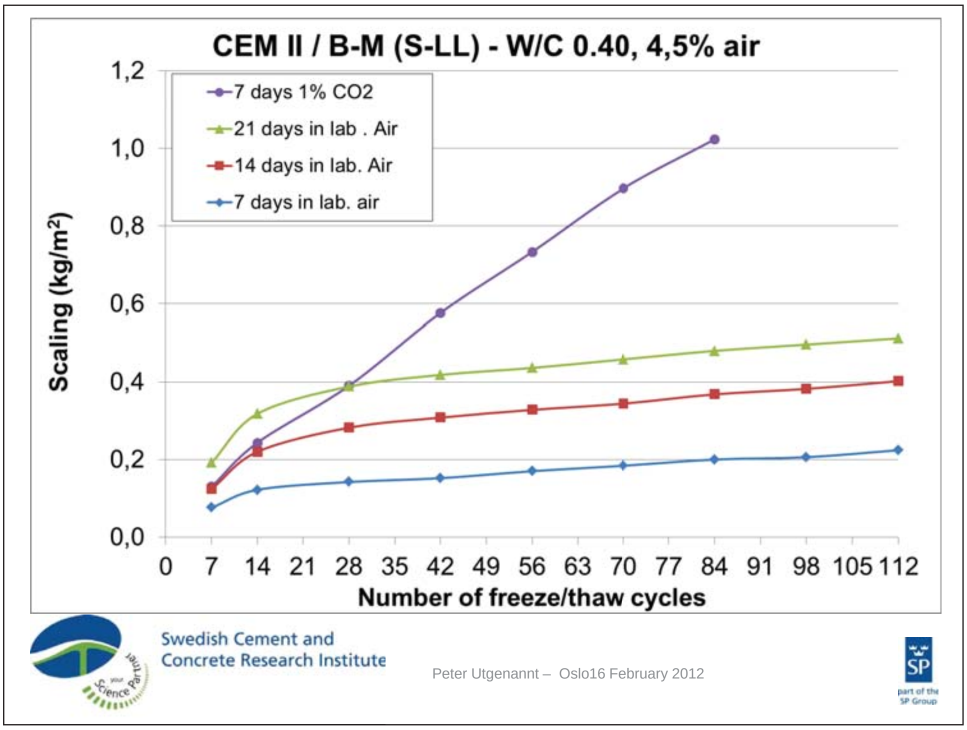
SP


CEM II / B-M (S-LL) - W/C 0.40, 4,5% air
7 days 1% CO2
21 days in lab . Air
14 days in lab. Air
7 days in lab. air
Scaling (kg/m²)
1,2
1,0
0,8
0,6
0,4
0,2
0,0
0 7 14 21 28 35 42 49 56 63 70 77 84 91 98 105 112
Number of freeze/thaw cycles
Swedish Cement and
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Conclusions

- After 14 years of exposure - Concrete with CEM I, CEM II/A-LL, CEM II/A-S, CEM I + 30 % slag and CEM I + 5 % silica as binder, with entrained air and w/b-ratio 0.50 or below, has good resistance to internal and external damage.
- Concrete with CEM III/B suffers from severe scaling even with a w/b-ratio of 0.50 and with entrained air.
- Ageing (carbonation) influences the scaling resistance, however different for different cement/binder types.

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Conclusions

Results from laboratory testing (CEN/TC 12390-9) classifies most concrete qualities correctly. However…

- For concrete with low w/b-ratio (CEM I and CEM II-A) and with no entrained air the laboratory test may underestimate the scaling resistance (experience after 14 years)
- For concrete with high/medium contents of slag (both with and without air) the results from laboratory testing may overestimate the scaling resistance.

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Conclusions

- In the revision of (CEN/TC 12390-9) changes should be made so that the effect of carbonation is better taken into account. For example a somewhat longer preconditioning time or conditioning in a somewhat increased CO_2 atmosphere (~1 vol %).

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Conclusions

More research is needed!

- How much slag is suitable in an aggressive environment with regard to salt/frost attack?
- Effect of different curing regimes?
- How is the scaling resistance of blended cements (slag/flyash/limestone filler) influenced by ageing?

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Predicting air entrainment and frost durability in fly ash concrete

Nordic workshop **"Durability aspects of fly ash and slag in concrete"** , Oslo 15th and 16th of February 2012

Stefan Jacobsen, Margrethe Ollendorff, Mette R. Geiker
Dept of Structural Engineering, NTNU,
Trondheim, Norway

Lori Tunstall, George W. Scherer
Princeton University, NJ, USA

1

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Air entrainment - why

- Air voids can protect concrete against frost- and salt scaling damage
  - Place of escape for frost-induced flow and unrestrained ice formation (Powers, Helmuth 1949, 1953)
  - Increased effective CTE in frozen air-entrained concrete reducing thermal incompatibility to ice (Scherer et al 2005 a,b,c, 2007, 2010)
  - Air void shell quality varies by AEA-paste interaction, affecting ice propagation from void into bulk paste (Scherer 2011 MPPS 15p.)
  - Reduced degree of saturation (Fagerlund 1971)

- *But* air voids cannot save insufficiently cured concrete, over-saturated concrete, concrete with damaged pore structure due to heat curing, deleterious ageing effects etc.

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Air entrainment and frost and salt scaling durability in Fly Ash Concrete:

- **WHEN sufficiently cured, FA concrete can be made durable against Frost and Salt scaling**
  - FA concrete as frost durable as OPC (14-28 d moist cure, ≥ 4 – 5 % air, spacing L ≤ 0.23 mm, spec surface α ≥ 0.25 mm^{-1}) V.Malhotra, A.Ramezanianpour Fly Ash in Concrete 2nd Ed Canmet MSL 94-45(1994), Jacobsen & Lahus ACI SP202 (2001) etc
  - FA concrete practically as salt frost scaling resistant as OPC (14-28 d moist cure, ≥ 5-6% air, spacing L ≥ 0.20 mm,specific surface α ≥ 0.25-30 mm^{-1}) though more variable Malhotra, Fly Ash in Concrete (1994), Bilodeau & Malhotra, Quebec (1993) etc
- **BUT (High Volume FA) Concrete: problem with low/slow curing**
- **AND FA Concrete: often difficult to entrain good air void system**

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Air Antraining Agents (AEA): what and how?

- AEA: mixtures of various surfactants with more or less confusing names (vinsol resin, tall oil, synthetic tenside etc)
- AEA structure: hydrophilic (anionic) «head» (to liquid) and hydrophobic hydrocarbon chain «tail» (to air)
- AEA function: reduce water-air surface tension, adsorb to solid surfaces, stabilize air in fresh concrete. (There might also be additional effects)
- Du&Folliard (2005) propose AEA-distribution in fresh concrete:

$$AEA_{added} = AEA_{interface} + AEA_{adsorbed\ on\ solid} + AEA_{liquid}$$

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Problem: AEA and Fly Ash with variable carbon

- Carbon (high surface) adsorbs AEA, reducing air entrainment (in addition to effect of adsorption on pozzolan (several studies)
- HOWEVER, admixture details often not known, see for example study on AEA-SP compatibility (Nkinamubanzi P.C, Bilodeau A., Joliceur et al 2003) or in new study on air pore structure with AEA and Polycarboxylate based SP (Vollset&Mortensvik 2011)
- SO, limited applicability for concrete technologists beyond what brand name to choose due to no generic information whatsoever of the AEA
- How to select AEA and to predict air entrainment?

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Foam Index (FI) – fast test of air entraining effect of binder/AEA combination

(Dodson 1990, gebler&Klieger 1983, Vestgarden 2005/ 2006, Harris et al 2008a,b,c etc)

- Shake water, binder powder and AEA (typically w/b = 2.5 for 15 sec)
- Observe the stability of the foam forming on top (typically 45 sec)
- Increase the AEA dosage drop-wise (often 20 µl 10 % AEA solution) and repeat "shake-and-wait-procedure" until a stable foam is reached
- FI = concentration of AEA (in ml/kg = µl/g) of binder as foam remains stable

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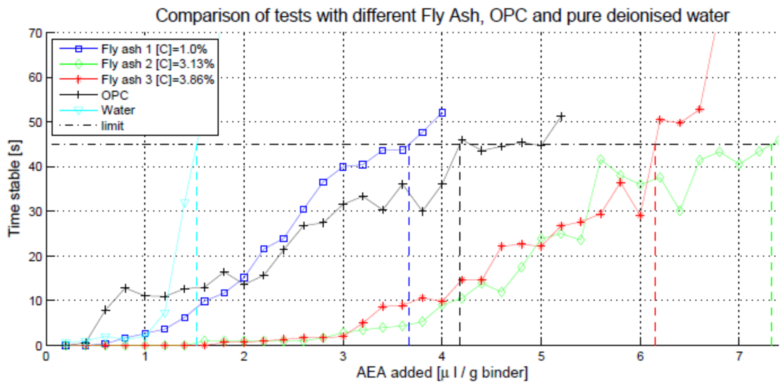
Foam Index - benchmark testing

Eur. FA, Norw. CEM 52.5, Sika Aer –S («synthetic tenside»)
(Ollendorff 2011)



(Sika Aer –S: recommended normal dosage = 0.01 – 0.08 % of cement weight = 0.1 – 0.8 µl/g, which is only ~1/10 of FI)

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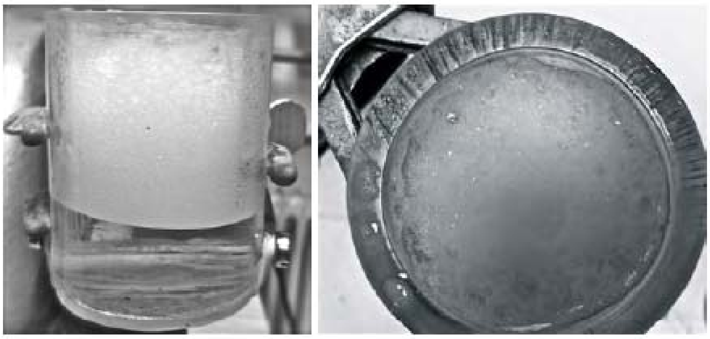

Figure 4.4: Foaming of pure water

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Figure 4.1: Foam propagation for high carbon ash, from left: initiation, filled surface, stable foam

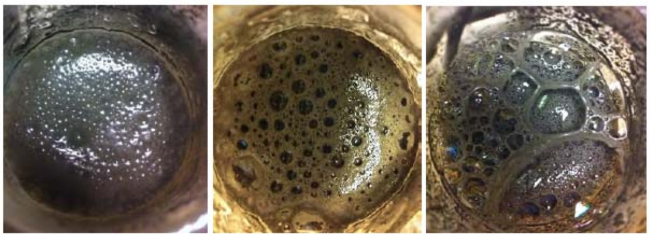

Figure 4.2: Typical foam structures, from left: fly ash 3, fly ash 2, fly ash 1

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Approach 1:
Use correlation FI – air entrainment in concrete

- Gebler & Klieger (w/b = 0.40 – 0.48, 307 kg/m^3 binder with 25 % FA 6 ± 1 % air): correlation FI – AEA dosage for 6 % air is $R^2 = 0.93$ for 10 ashes /1 OPC reference («Dodson-Meiniger type»: 420 ml container, w/b = 2.5, 15 s shake/45 s rest)
- Vestgarden (2006) (w/b = 0.42, 20 % FA, 0.18 kg/420 kg binder incl 5 % SF): best correlation FI (automated shaker) - fresh air void content at constant AEA dosage after 10 minutes is $R^2 = 0.84$ for 9 ashes/1 OPC reference
- Harris et al (2008a) (w/b = 0.45, 335 kg binder with 20 % FA and 6.0 ± 1.0 % air): best correlation FI – AEA dosage for 6 % air is $R^2 = 0.94$ for 4 ashes manual bottle shake test (10 g powder, w/b = 2.5, Ø = 45 mm, V = 132 ml, 15 s shake/45 s rest)

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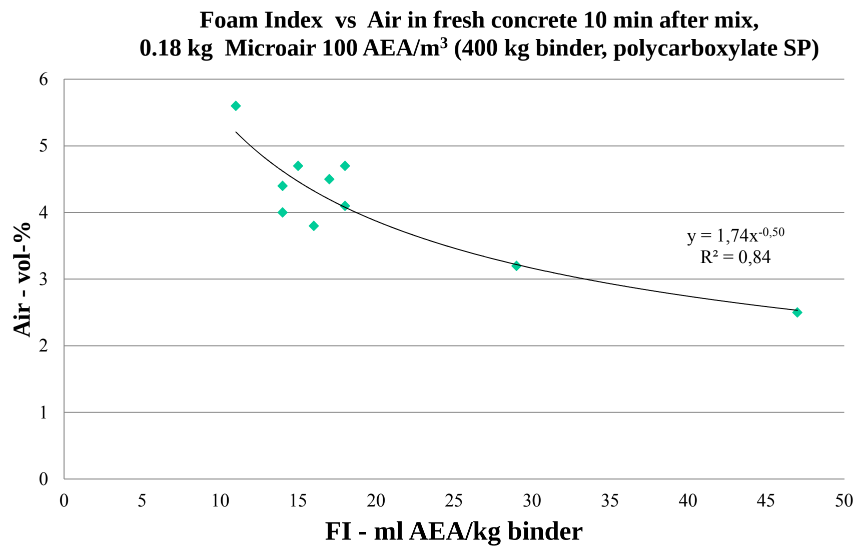
FI –Air in concrete - data byVestgarden (2006)



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Approach 2: Adsorption and «fingerprinting» combined with Foam Index testing

- TGA and NMR for AEA adsorption and fingerprinting
  - High and low C fly ash
  - Different AEA (Saponified Rosin, Synthethic Olefin Sulfonate, Saponified Tall Oil, Neutralized Vinsol Resin)
- Foam index
  - High and low C fly ash
  - AEA with high and low adsorption
  - FI test – standard
  - FI test short time – "a lot AEA in"
  - FI test – wait 1 h after short test – foam stability? add AEA if necessary

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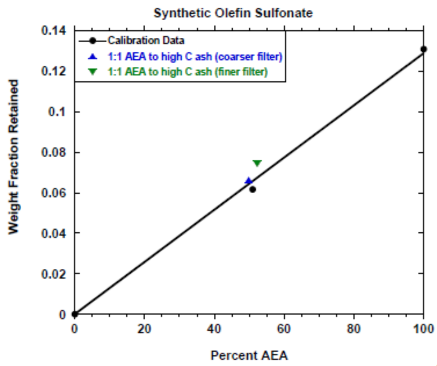
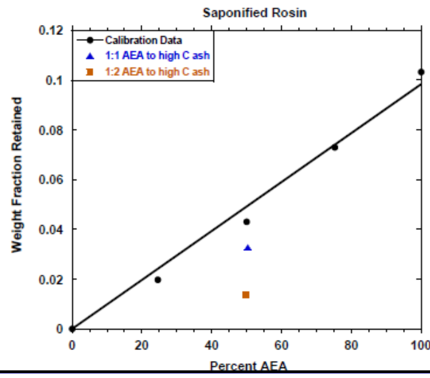


TGA to detect Adsorption of
AEA on FA
Tunstall&Scherer (2012)

Clear differences on high-C FA
- SOS: no adsorption
- SR: adsorption



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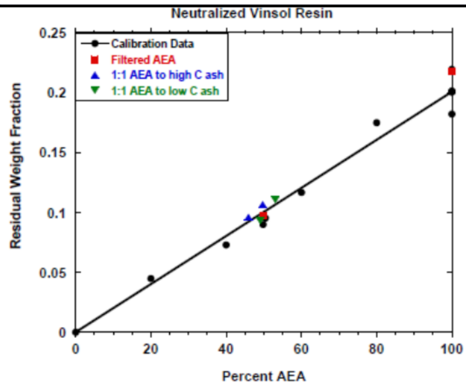
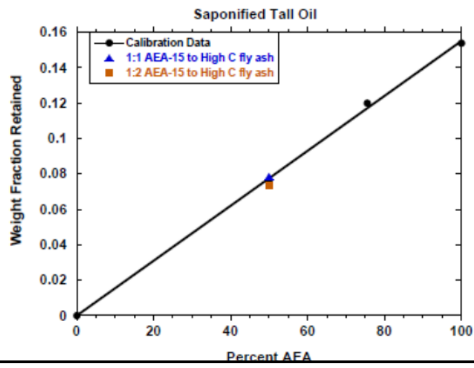


Tunstall&Scherer (2012) (contd.):
Neither Vinsol Resin nor Tall Oil have adsorption detectable with TGA



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NMR spectra showed clear shifts for SR after adsorption on ash (whereas practically no shifts were observed on SOS which did not adsorb)

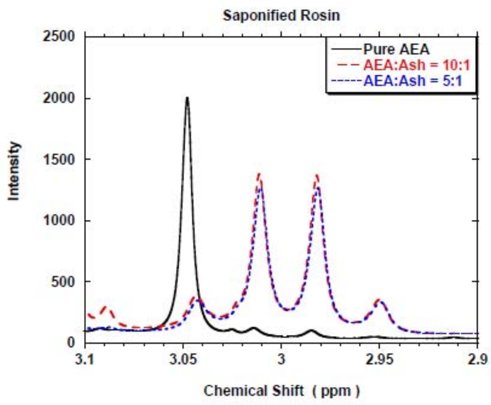

Figure 4. [1]H NMR spectra for pure saponified rosin AEA, and filtrate of AEA following mixing with high-carbon fly ash at mass ratios of AEA:Ash = 10:1 and 5:1. Peak centered near 3.05 ppm disappears and new peaks near 3.0 arise following exposure to the ash.

(the identity of the adsorbed species will be determined by further NMR studies)

Tunstall&Scherer (2012)

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FI-tests performed on selected materials from adsorption (TGA, NMR) study

- Standard: 20 µL drops, 15 s shake/45 s wait
- Short time – «a lot in at once»: ½ amount of FI + 15 sec shake, then 20 µL drops, 15 s shake/45 s wait
- Prolonged time: after «Short time»: seal and wait 1 h, observe foam stability, if necessary add 20 µL drops, 15 s shake/45 s wait

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Table 4.3.2: FIoam index for standard and "short time" tests

AEA	Concentration [%]	Fly ash (LOI%)	Procedure	Foam Index μl/g ash
SR	40	High carbon(11.73)	Std	192.8
SR	40	High carbon(11.73)	Short	104
SR	40	Low carbon(2.40)	Std	18.4
SR	40	Low carbon(2.40)	Short	17.6
SOS	40	High carbon(11.73)	Std	40
SOS	40	High carbon(11.73)	Short	36
SOS	40	Low carbon(2.40)	Std	4.8
SOS	40	Low carbon(2.40)	Short	4.8
NVR	*40*	*High carbon(11.73)*	Std	*32*

Ollendorff (2011)

Table 4.3.3: Foam Index for "prolonged time" tests

AEA	Fly ash(LOI%)	Stable time [s]	Additional ml/ g ash	New FI μl/ g ash	Increase %
SR	High carbon(11.73)	22.85	48	152	46.1
SR	Low carbon(2.40)	35	4.8	22.4	27.3
SOS	High carbon(11.73)	$\geq$45	0	36	0
SOS	Low carbon(2.40)	$\geq$45	0	4.8	0

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Table 4.3.4: Comparison of test time for the different procedures and their respective FI

		Exposure time and Foam Index for each test regime					
		Standard		"Short"		long	
AEA	Fly ash(LOI%)	Time Minutes	FI μl/ g ash	Time Minutes	FI μl/ g ash	Time Minutes	FI μl/ g ash
SR	High carbon(11.73)	180	192.8	3	104	73	152
SR	Low carbon(2.40)	12	18.4	6	17.6	74	22.4
SOS	High carbon(11.73)	50	40	5	36	65	36
SOS	Low carbon(2.40)	5	4.8	4	4.8	64	4.8

Ollendorff (2011)

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Conclusion

- FI high for US AEA that adsorbs (SR – Saponified Rosin), both on US high carbon FA (FI very high = 192.4 µL/g) and on US low carbon FA (FI quite high = 18.4 µL/g compared to FI in benchmark test on 3FA, 1OPC and one AEA from Norwegian market (FI = 3.7-7.3)).
- FI low for US AEA that does not adsorb (FI = 4.8 for SOS – Synthetic Olefin Sulfonate) on US low carbon FA. FI also comparatively low for US AEAs that do not adsorb (FI = 40 and 32 for SOS and NVR - Neutralized Vinsol Resin) for US high carbon FA.
- FI – time dependency and foam stability affected by adsorption:
  - FI depends on time for the AEA that adsorbs (SR):
    - For "short" testing time FI always reduces compared to "std"
    - For "prolonged" time FI always increases compared to "short"; i.e. AEA must be added to retrieve the foam lost after 1 h waiting
  - FI is unaffected by time for the AEA that does not adsorb (SOS), i.e. foam remains stable after 1h.
- Air entraining mechanisms in FI test and fresh concrete are different. Still combination adsorption-FI as well as correlation FI- air in fresh concrete indicate usefulness of the FI test
- Further research on the function of air voids with FA and AEA needed

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Business from technology

The effect of by-products on frost-salt durability of aged concrete

Durability aspects of fly ash and slag in concrete
Nordic Workshop, Oslo-Norway, 15-16 February 2012

Miguel Ferreira, Markku Leivo & Hannele Kuosa
VTT Technical Research Centre of Finland

Contents

1. DuraInt Project
2. Motivation & Goals
3. Testing procedures
4. Concrete mixes
5. Results
6. Final comments

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DuraInt Project
Effect of interacted deterioration parameters on service life of concrete structures in cold environments

TEKES

A! Aalto University School of Science and Technology

www.vtt.fi/sites/duraint

- Reports for field & laboratory testing, deterioration & service life modelling
- Excels database with testing results for different projects & field stations

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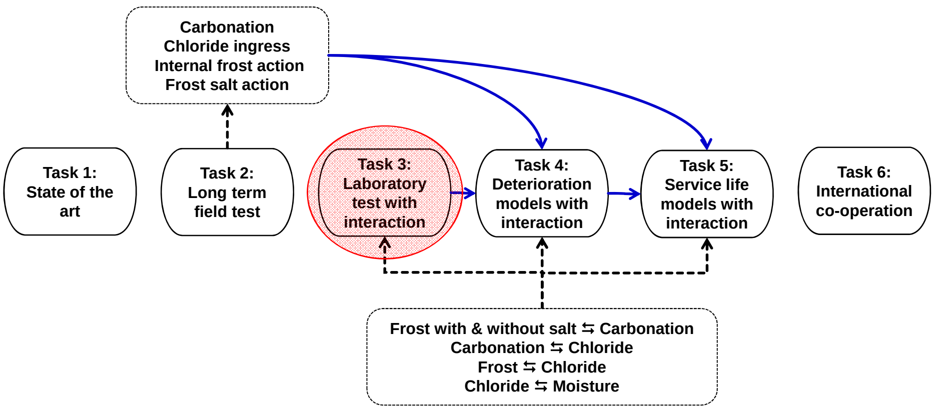
DuraInt Project – Overview



Motivation & Goals

- Concrete performance based on single deterioration mechanism
- *In situ* concrete subject to simultaneous exposure to several deterioration mechanisms
- Ageing influenced by hydration, drying, carbonation, etc.
- Research on ageing has shown it to be both positive or negative
    - Depends on composition, testing procedures, ageing time, etc.
    - What is the effect of ageing on performance with different cements, additions, additives, air contents, etc.?
- To understand the effect that varying surface ageing conditions (carbonation and drying) have on frost-salt scaling

Testing procedures

- Compressive strength – 150mm cubes at 28 days
    - SFS EN 12390-3:2009
- Fresh air and workability
    - SFS EN 12350-7:2009 & SFS EN 12350-2:2009
- Air void parameters of hardened concrete – thin section analysis
    - VTT TEST R003:2000 – similar to ASTM C 457:2010
- Frost-salt scaling resistance – slab test with 3% NaCl & 56 cycles
    - CEN/TS 12390-9:2006
- Resistance to carbonation – 1% CO_2 for 56 days
    - Based on SFS EN 13295:2004

Testing procedures

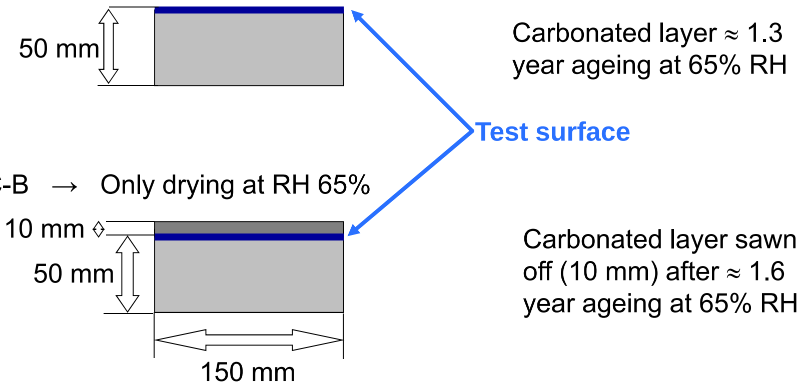
EC-A
- Standard procedure after casting → Frost-salt testing (56 cycles)

EC-C
- At 65% RH, ageing with natural carbonation from 21 d until 1.2 – 1.3 years → Frost-salt testing (56 cycles)

EC-B
- At 65 % RH from 21 d until ca. 1.6 years → 10 mm layer was sawed off, i.e. ageing without carbonation → Frost-salt testing (56 cycles)

Testing procedures

- EC-C → Carbonation + drying at RH 65%
- EC-B → Only drying at RH 65%



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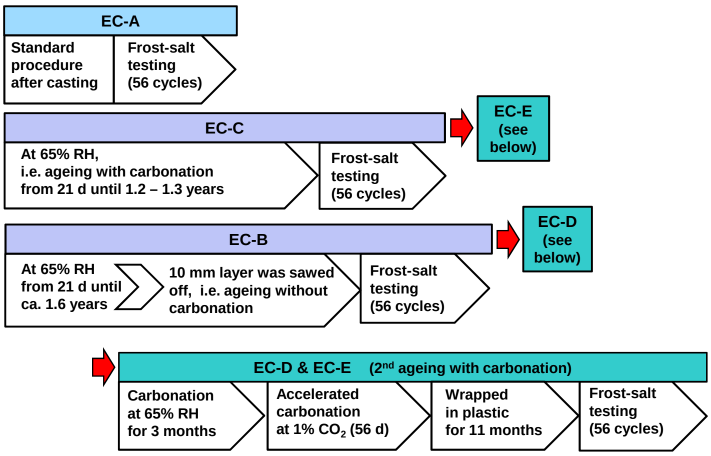
Testing procedures



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Concrete mixes

Mix.	CEM Types	Binder kg/m^3	Aggreg. kg/m^3	w/b ratio -	Fresh air %	Slump mm
M1	I 42,5 N-SR	387	1796	0.42	5.9	115
M2	II/A-M(S-LL) 42,5 N	428	1709	0.42	5.9	180
M3	II/A-LL 42,5 R	241	1748	0.42	5.0	140
M4	I 52,5 R	417	1737	0.42	5.5	80
M5	II/A-LL 42,5 R + 50% BFS	434 (217)	1725	0.42	6.1	150
M6	II/A-LL 42,5 R + 23% FA	450 (106)	1706	0.45	5.0	170

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Some BFS & FA characteristics

Add.	CaO	SiO_2	Al_2O_3	MgO	Na/K_2O	γ_D Kg/m^3	Blaine fineness m^2/kg
BFS	40	34	9.3	11	0.47/0.47	2.97	400
FA	4-7	45-55	20-30	3-5	1-2	2.20	≈ 250

- BFS – Finnsementti KJ400
- FA – Fineness N, Class A (EN 450-1:2005)

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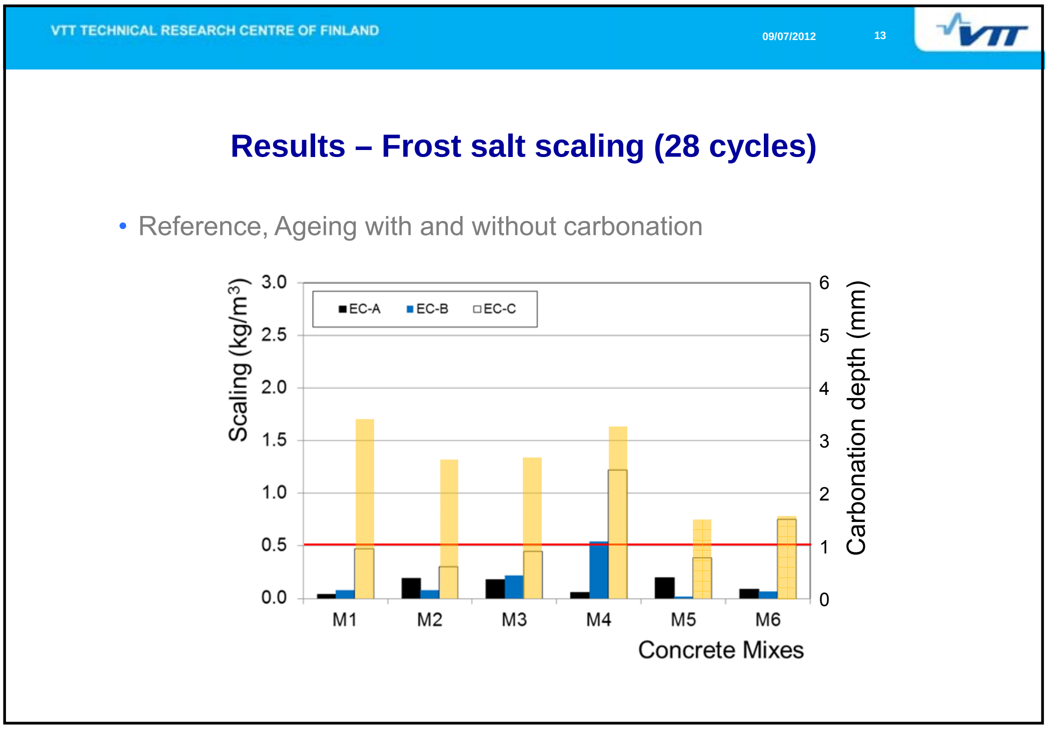
Results – Compressive strength & air void parameters

Mix.	CEM types	$R_{C28days}$ MPa	Pores <0.3mm %	Specific surface area kg/m^3	Spacing factor mm
M1	I 42,5 N-SR	46.4	3.5	16	0.35
M2	II/A-M(S-LL) 42,5 N	38.0	2.8	21	0.28
M3	II/A-LL 42,5 R	41.2	2.2	28	0.24
M4	I 52,5 R	58.5	0.6	34	0.33
M5	II/A-LL 42,5 R + BFS	46.0	2.6	37	0.18
M6	II/A-LL 42,5 R + FA	54.6	1.6	27	0.30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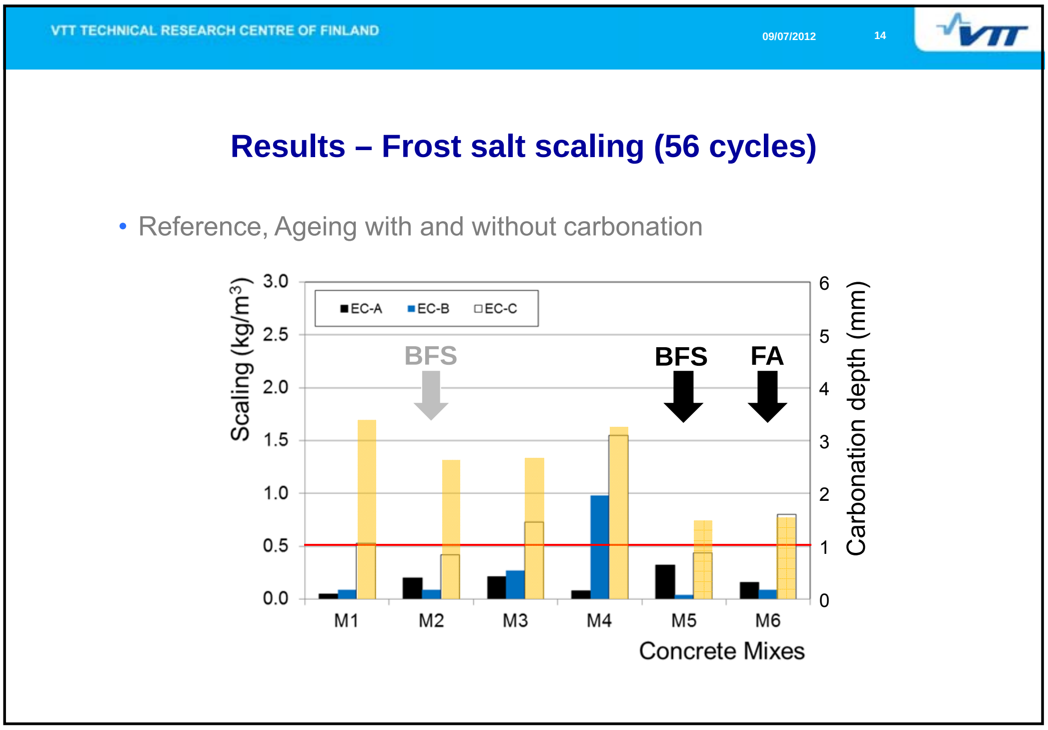
09/07/2012
13
VTT
Results – Frost salt scaling (28 cycles)
• Reference, Ageing with and without carbonation
EC-A
EC-B
EC-C
Scaling (kg/m³)
Carbonation depth (mm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
6
5
4
3
2
1
0
M1
M2
M3
M4
M5
M6
Concrete Mixes


VTT TECHNICAL RESEARCH CENTRE OF FINLAND
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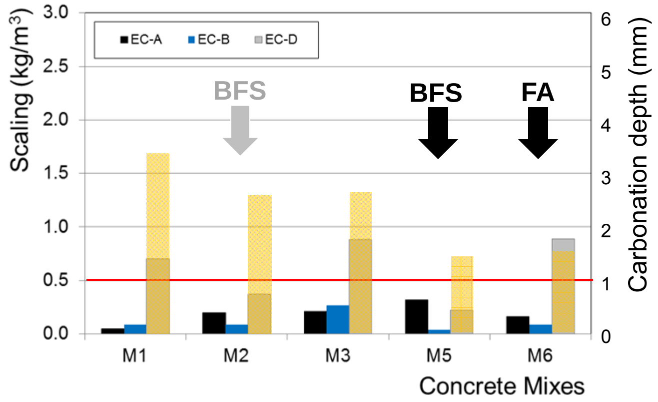
14
VTT
Results – Frost salt scaling (56 cycles)
• Reference, Ageing with and without carbonation
EC-A
EC-B
EC-C
BFS
BFS
FA
Scaling (kg/m³)
Carbonation depth (mm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
6
5
4
3
2
1
0
M1
M2
M3
M4
M5
M6
Concrete Mixes

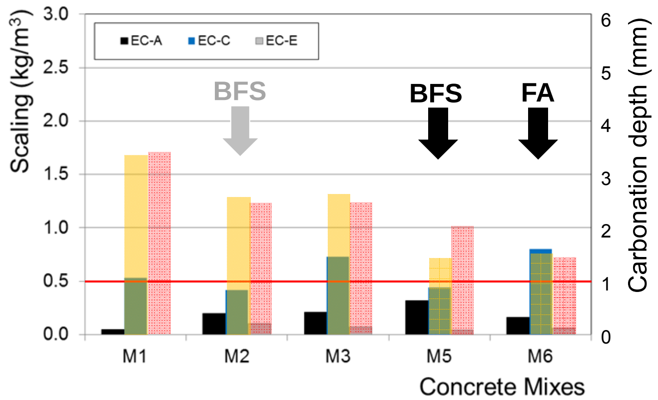
Results – 2nd round frost salt scaling (56 cycles)

- Reference, 1st round without carbonation, 2nd round with carbonation



Results – 2nd round frost salt scaling (56 cycles)

- Reference, 1st and 2nd round with carbonation



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Final Comments

- Ageing testing procedure influences the frost salt scaling performance of the concrete – not considered in the reference test setup
- Carbonation influences negatively all tested concretes – should be compared only if identical quality of air void structure

- BFS seems to improve performance in tested concretes after ageing – early age frost salt performance testing not favorable
- FA performance inferior to BFS, but lower quality air void system could be influencial factor

Thank-you!
Kiitos!

VTT creates business from technology

PERFORMANCE OF CONCRETE MIXED WITH FLY ASH OR BLAST FURNACE SLAG

Anders Lindvall
Ingemar Löfgren
Oskar Esping

THOMAS CONCRETE GROUP AB

February 2012

Background

- Interest of using industrial bi-products in concrete exposed in severe environments in Sweden
  - Along thaw-salted road and in marine environments.
    - Exposure classes (EN 206-1). XS 1-3, XD 1-3 and XF 2 & 4.
    - Traditionally concrete made of Portland Cement (CEM I).
  - Partly replace Portland cement with
    - Pulverized Fly Ash (PFA).
    - Ground Granulated Blastfurnace Slag (GGBS).
    - Silica fume (SF).
- Why use industrial bi-products in concrete?
  - Decreased usage of energy.
  - Decreased environmental impact.
  - Improve properties of concrete.

THOMAS CONCRETE GROUP AB

February 2012

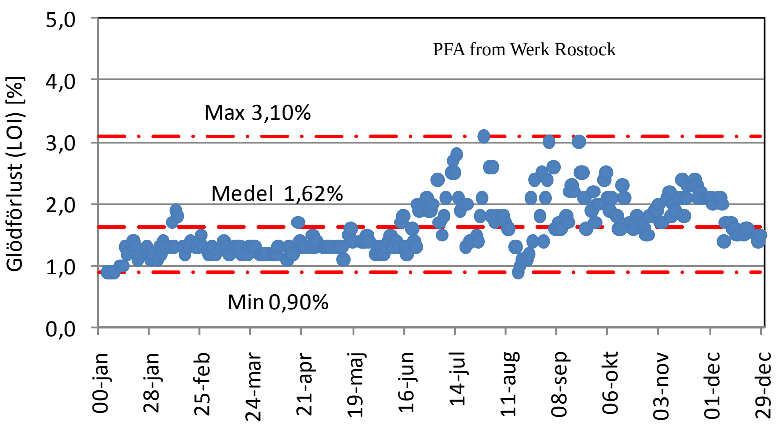
PFA and GGBS in concrete

- Alternatives for usage in concrete
  - Additions in the cement. Portland composite cements (CEM II) and Slag cements (CEM III). Regulated in EN 197-1.
  - Additions at the concrete mixing plant. Regulated in EN 206-1, EN 450-1 and EN 15167-1.
- Properties of PFA and GGBS regulated in EN 405-1 and EN 15167-1
  - Historically variations in quality $\Rightarrow$ variations in properties of concrete.
  - Chemical composition, e.g. mineral composition and LOI.
  - Physical properties, e.g. fineness.
  - Properties when combined with cement, e.g. setting time and AI.
- Regulations in EN 206-1 (addition at the mixing plant)
  - Equivalent Concrete Performance Concept (ECPC). Equivalent performance (e.g. durability) compared to a reference concrete.
  - Concept with *k*-factors. Performance of different binders is described with *k*-factors (normally calibrated against compressive strength of mortar or concrete).

THOMAS CONCRETE GROUP AB

February 2012

Loss on ignition for PFA



Data from Thomas Cement (2012)

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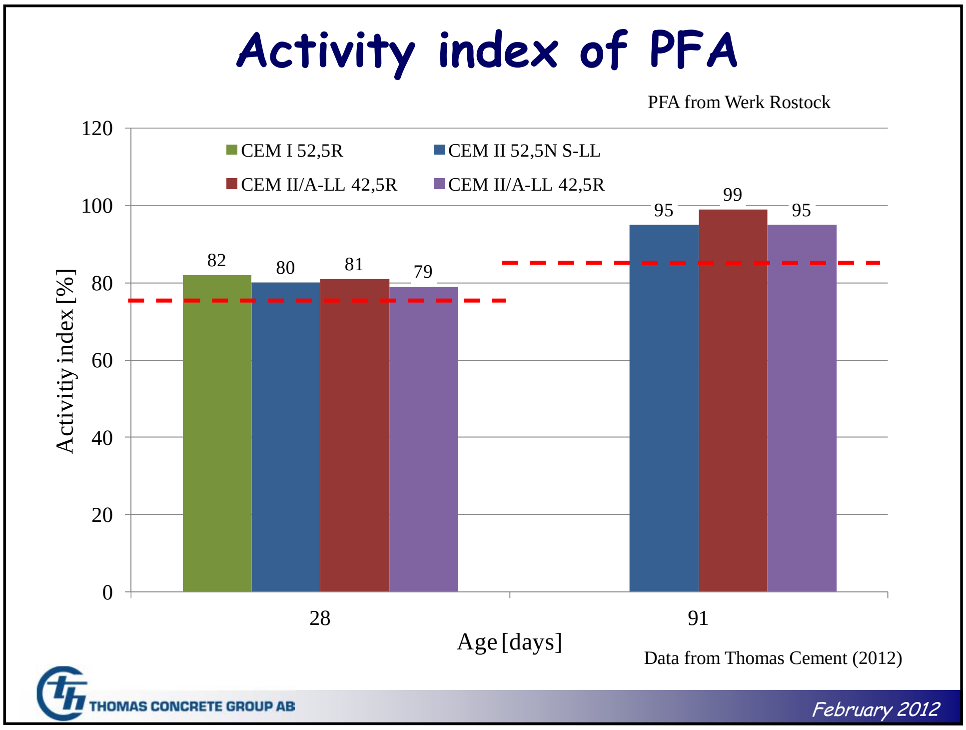
Activity index of PFA
PFA from Werk Rostock
CEM I 52,5R
CEM II 52,5N S-LL
CEM II/A-LL 42,5R
CEM II/A-LL 42,5R
Activity index [%]
120
100
80
60
40
20
0
82
80
81
79
95
99
95
28
91
Age [days]
Data from Thomas Cement (2012)
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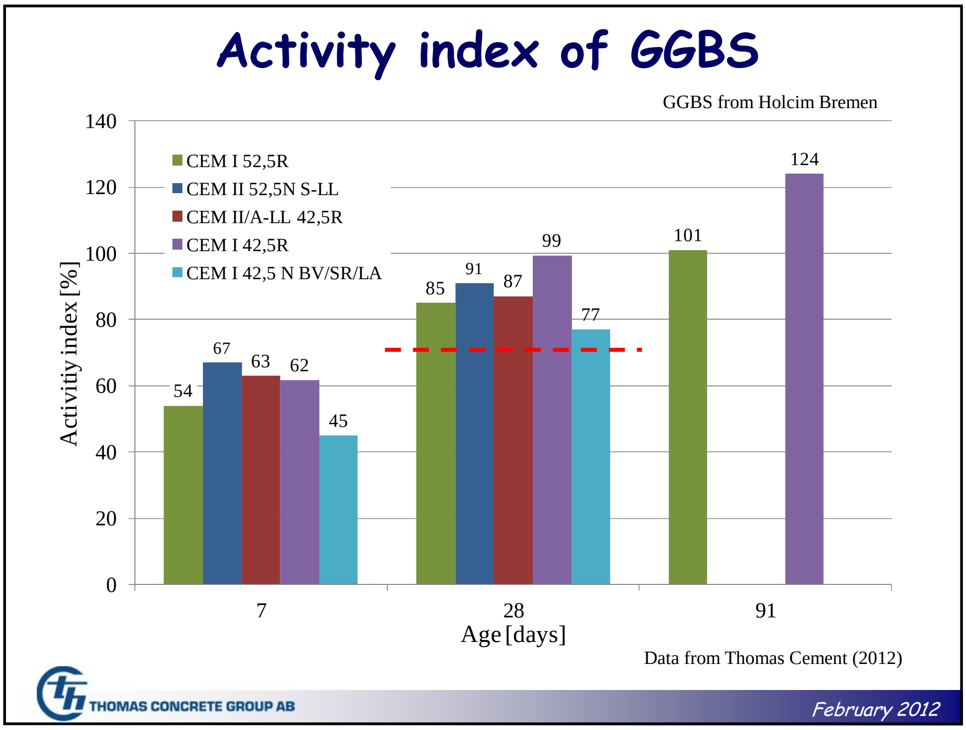
Activity index of GGBS
GGBS from Holcim Bremen
CEM I 52,5R
CEM II 52,5N S-LL
CEM II/A-LL 42,5R
CEM I 42,5R
CEM I 42,5 N BV/SR/LA
Activity index [%]
140
120
100
80
60
40
20
0
54
67
63
62
45
85
91
87
99
77
101
124
7
28
91
Age [days]
Data from Thomas Cement (2012)
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Swedish regulations

- SS 13 70 03. Application of EN 206-1 in Sweden.
- AMA Anläggning. Regulations for infrastructure structures.

	Allowed additions of PFA		**of GGBS**
Exposure class	SS 13 70 03 [wt-% of CEM I]	AMA Anläggning [wt-% of cement]	SS 13 70 03 [wt-% of CEM I]
X0 , XA 1	50	11	230
XC 1-2	50	11	150
XC 3-4, XS 1-2, XD 1-2, XF 1-3, XA 2	50	11	50
XS 3, XD 3	25	11	25
XF 4	25	6	25
XA 3		11	

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Investigations

- Investigate the properties of concrete mixed with combinations of Portland cement and PFA or GGBS
  - Additions according to SS 13 70 03. Exposure class XF 4.
  - Effect of additives described with the *k*-factor concept (PFA, *k*=0.4 and GGBS, *k*=0.6).
- Tests made
  - Compressive strength. EN 12390-3.
  - Resistance against chloride ingress. NT Build 492.
  - Frost resistance. SS 13 72 44 (EN 12390-9).
- Three projects
  - Master Thesis . Knutsson (2010).
  - Research project financed by SBUF (Swedish construction industry's organisation for research and development). Lindvall (2012).
  - Master Thesis. Correia (2012).

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Investigations of Knutsson (2010)

- Concrete compositions. $(w/c)_{eq}$=0.45
  - Portland cement (CEM I) mixed with PFA
    - No addition of PFA (reference).
    - 20 wt-% PFA of CEM I. *k*=0.4.
    - 20 wt-% PFA of CEM I. *k*=1.0.
  - AEA used to mix in extra air.
    - Air content in fresh concrete=4.3-4.8 %.
    - Dosages of AEA needed to be increased when PFA was added.
    - Combination with VR to achieve reasonable dosages.
- Curing conditions
  - Standard. +20°C. 28-90 days.
  - Increased temperature. +55°C. 28-42 days

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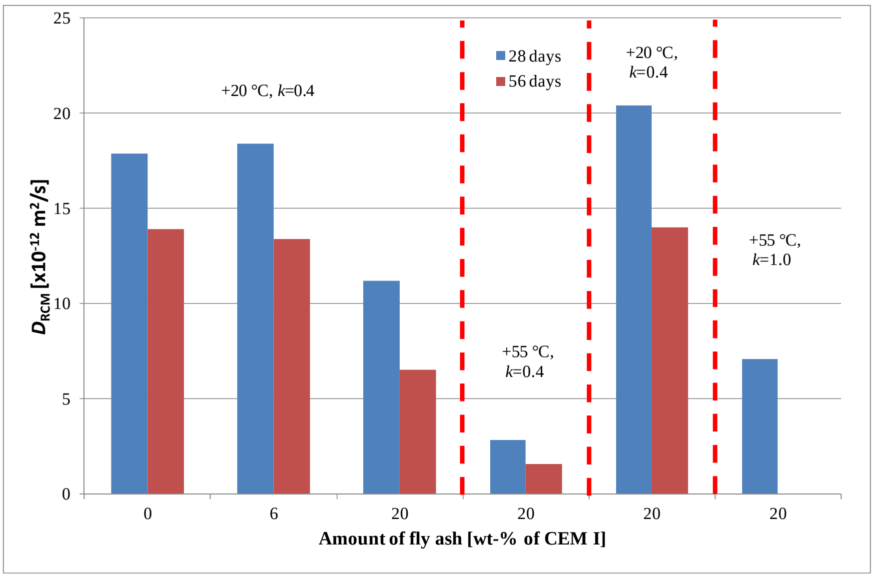
Results – Knutsson (2010)



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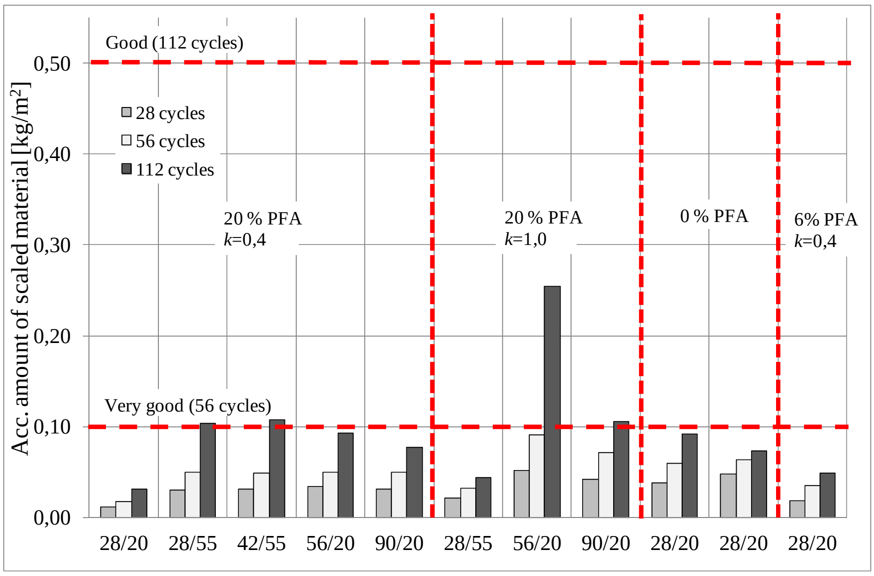
Results – Knutsson (2010)



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Investigations of Lindvall (2012)

- Concrete compositions. $(w/c)_{eq}$=0.40-0.50
  - Portland cement (CEM I) mixed with PFA
    - No addition of PFA (reference).
    - 6-33 wt-% PFA of CEM I. *k*=0.4.
  - Portland limestone cement (CEM II) mixed with PFA
    - No addition of PFA (reference).
    - 25wt-% PFA of CEM I. *k*=0.4.
  - AEA used to mix in extra air.
    - Air content in fresh concrete=4.8-5.9 %.
    - Dosages of AEA needed to be increased when PFA was added.
    - Combination with VR to achieve reasonable dosages.
- Curing conditions
  - Standard. +20°C. 28 days.
  - Prolonged. +20°C. 56 days.

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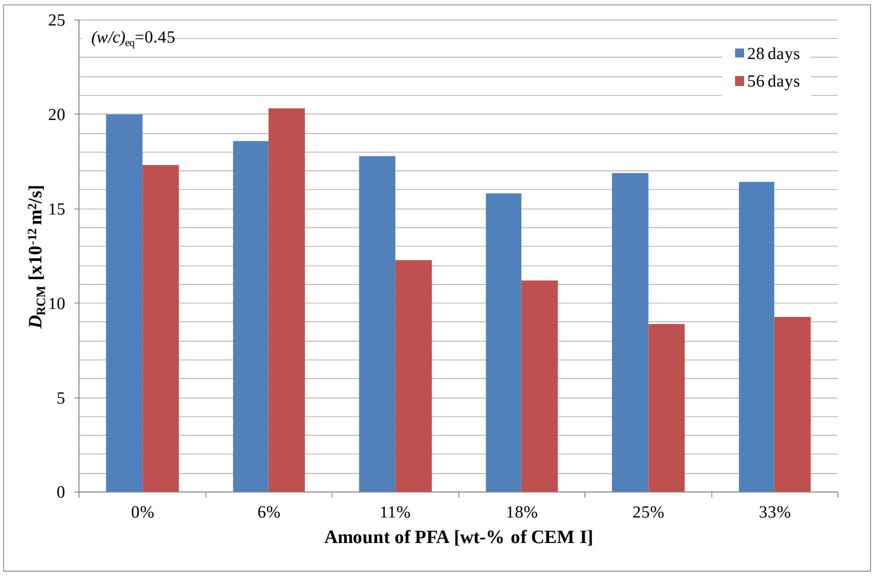
Results – Lindvall (2012)



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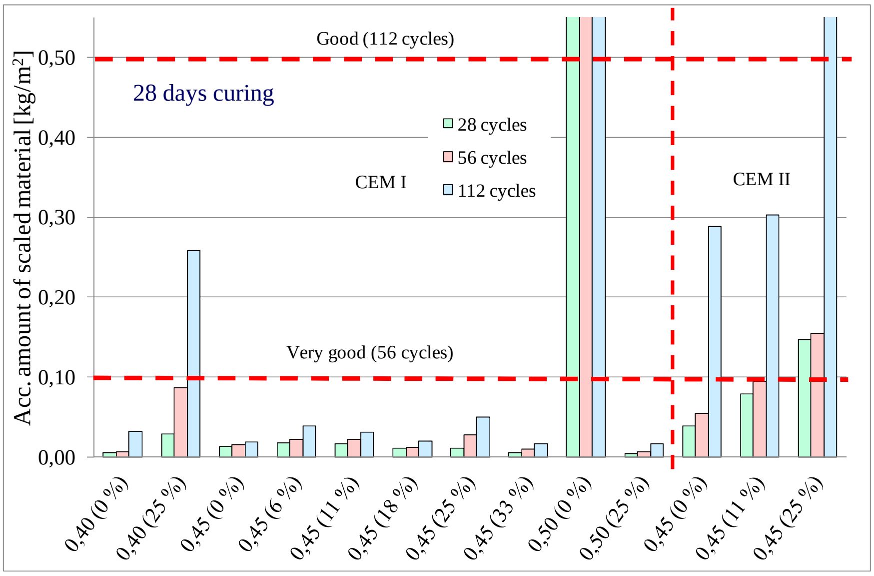
Results – Lindvall (2012)



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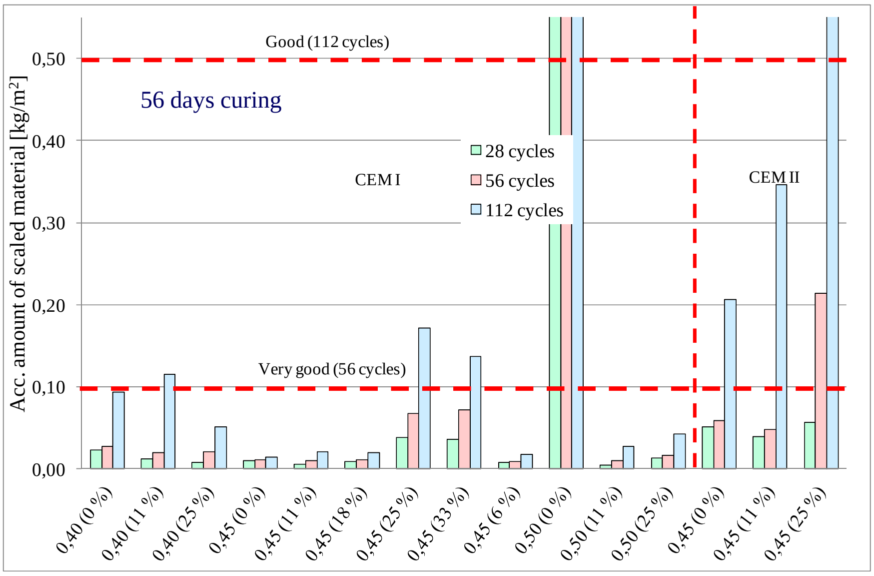
Results – Lindvall (2012)



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Conclusions – concrete with PFA

Concretes with additions of PFA (up to 33 wt-% of CEM I and *k*=0.4) have comparable properties as CEM I concretes.

- Strength. At 28 days equal, if *k*=0.4.
- Frost resistance. Very good, as long as the air pore system in the concrete is good. Extra air mixed in with AEA.
  - Higher dosage of AEA required when PFA is added.
  - Prolonged curing decreases frost resistance when PFA is added.
  - If *k*=1.0 frost resistance is decreased.
  - If CEM II is used the frost resistance is decreased.
- Resistance against chloride ingress.
  - Significantly improved compared to Portland cement concretes.
  - Prolonged curing increases resistance against chloride ingress.
  - If *k*=1.0 frost resistance is decreased (equal to CEM I concretes).
  - If CEM II is used the resistance against chloride ingress increases.

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Recommendations – concrete with PFA

- Concretes with additions of PFA have similar properties compared to Portland cement concretes
  - Properties of PFA according to EN 450-1.
  - Additions of PFA according to SS 13 70 03.
- Allowed additions of PFA
  - The regulations in SS 13 70 03 are reasonable, but in some exposure classes they are too conservative.
  - The regulations in AMA Anläggning are considered far too conservative
    - Are counteracting the positive effects of additions of PFA.
    - Are proposed to be revised so they harmonize with the regulations SS 13 70 03.

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Investigations of Correia (2012)

- Concrete compositions. $(w/c)_{eq}$=0.45
  - Portland cement (CEM I) mixed with GGBS
    - No addition of GGBS (reference).
    - 25-100 wt-% GGBS of CEM I. k=0.6.
  - AEA used to mix in extra air.
    - Air content in fresh concrete=4.4-5.5 %.
    - Dosages of AEA needed to be somewhat increased when GGBS was added.
- Curing conditions
  - Standard and prolonged. +20°C. 28 and 56 days.
  - Heat and prolonged. +55°C. 28 and 56 days.

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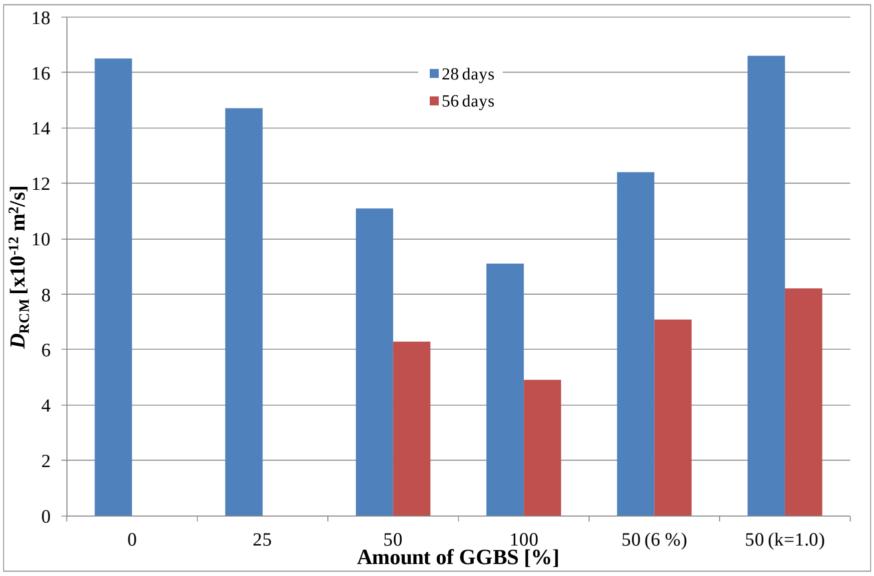
Preliminary results – Correia (2012)



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Thank you for the attention

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February 2012

Concrete Freeze-Thaw Scaling Resistance Testing

Experience and Development of a Testing Regime & Acceptance Criteria

Oslo, February 16th 2012, Terje F. Rønning

NORCEM
HEIDELBERGCEMENT Group

Background agenda

- European request of alternative, “milder” testing procedure & criteria than the current
  - CEN/TS 12390-9:2006
  - ► CEN TC 51 (+104) WG 12 / TG 4 re-awaken
- Future cement and concrete design & application with “different” properties development rate
- Norwegian current regulations for non-NA-adopted cement types or k x [additions] containing concrete (Application : Buildings or Engineering structures) :
  - W/C-ratio = 0.45 (0.40) + min. 4 % Air void content
  - Approval testing with 3 % NaCl
  - Test duration 56 or 112 F-T cycles
  - No formal opening of non-saline testing
  - Scarce experience of non-saline testing or Field/Lab relation

Side 2 - 2012-02-16
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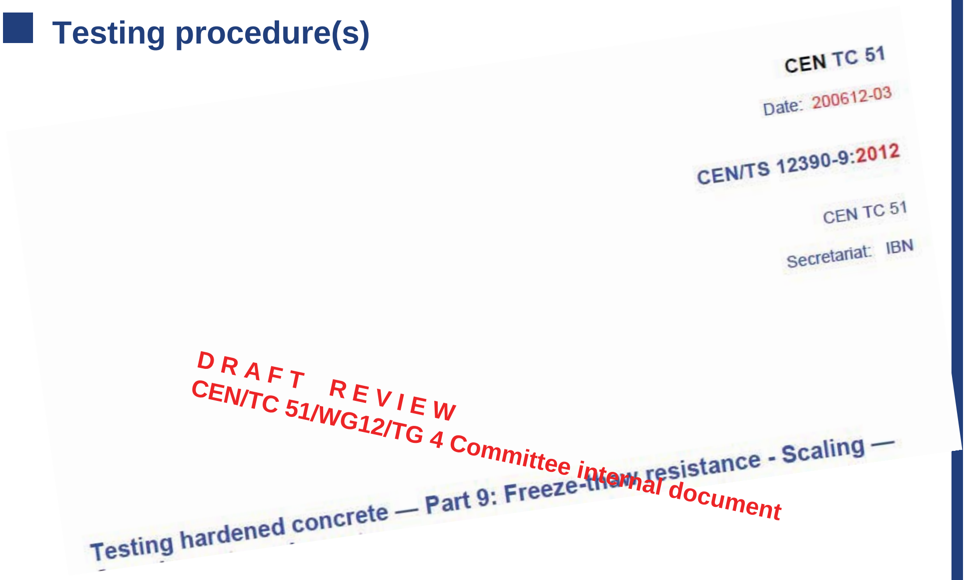
Testing procedure(s)



CEN TC 51

Date: 200612-03

CEN/TS 12390-9:2012

CEN TC 51

Secretariat: IBN

D R A F T R E V I E W

CEN/TC 51/WG12/TG 4 Committee internal document

Testing hardened concrete — Part 9: Freeze-thaw resistance - Scaling —

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Proposed "Market needs" adoption

ANNEX A : Alternative application

Alternative application may follow from specific objectives, such as but not limited to :

- Adoption of the testing method for concrete product testing, on samples with different geometry
- Investigation of concrete qualities with other age dependent properties development than those for which the testing methods was originally developed
- Adoption of the testing method for regional application of scaling acceptance limits, and in particular ;
- Such adoption with differentiation of severity of exposure conditions
- Adoption of the basic principles of the testing method but for research on certain mechanistic phenomena

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Proposed "CEN Market needs" adoption – Stage 1

ANNEX A : Alternative application

Alternative application may follow from specific objectives, such as but not limited to :

- Adoption of the testing method for concrete product testing, on samples with different geometry
- Investigation of c **other age dependent properties development** ich the testing methods was
- Adoption of the limits, and in particular ;
- **acceptance limits – differentiation of severity**
- Such adoption
- Adoption of the basic principles of the testing method but for research on certain mechanistic phenomena

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Adoptions Stage 1 : Concerns

- **other age dependent properties development**
  - **Deviation from standard age testing initiation :**
  - **Change in moisture history and level of carbonation may apply (Significance of which is explained)**
- **acceptance limits – differentiation of severity**
  - **Test results acceptance limits are not normally (…) applied in testing procedures.**
  - **This point disappointedly escapes several of those using this CEN/TS. NA responsibility !**
  - **Guidance to be provided : Nos. of F-T cycles may deviate from 56 but should always be 14 or more. Implications on statistics.**

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Adoptions Stage 1 : Concerns

- acceptance limits – differentiation of severity - Cont.
  - The temperature cycle shall not be changed ! (request from many parties) : Will significantly increase scatter !

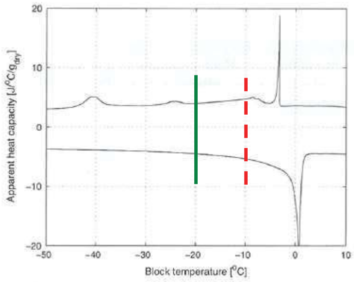

Fig. 11 Heat flow (given as apparent heat capacity) as a function of temperature. Cement paste, w/c = 0.5 after 75 days of hydration at 15°C [31]

Geiker et al, 2008

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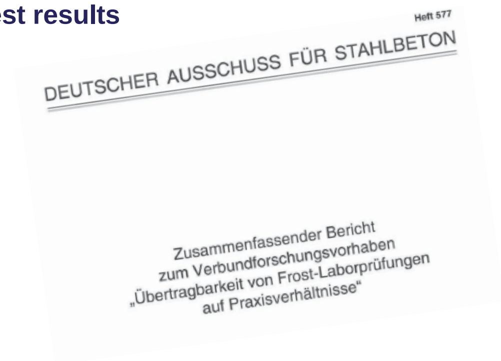
Adoptions Stage 2 : Concerns Lab/Field Relation

- XF 3 : Nos. of F-T cycles must be defined
  - Nos. of F-T cycles must be defined ?!
  - Definition of degree of saturation – in relation to field service conditions - prior to testing ?
  - Slowly developing binders : Do consider realistic degree of hydration for the frost exposure "load", including the influence of carbonation on the moisture exchange and F-T test results


Heft 577
DEUTSCHER AUSSCHUSS FÜR STAHLBETON

Zusammenfassender Bericht
zum Verbundforschungsvorhaben
„Übertragbarkeit von Frost-Laborprüfungen
auf Praxisverhältnisse"

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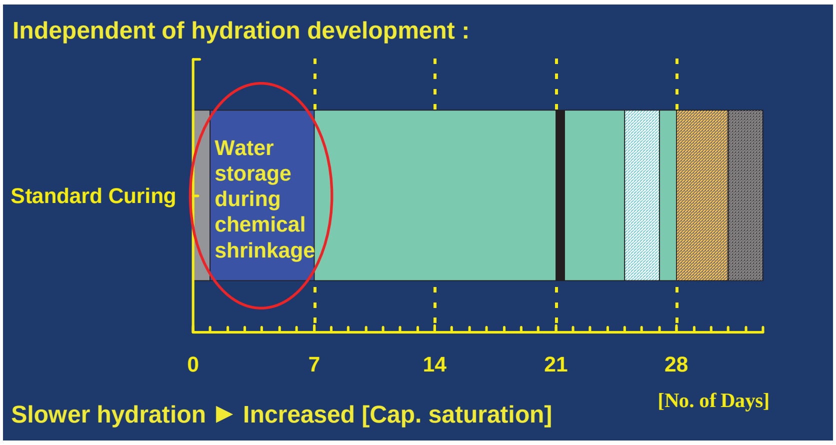
A key issue for Testing Performance - Moisture history, exposure & properties



Some of this w-filled volume would otherwise not be available to capillary suction – but possibly by F-T "pumping" under water.

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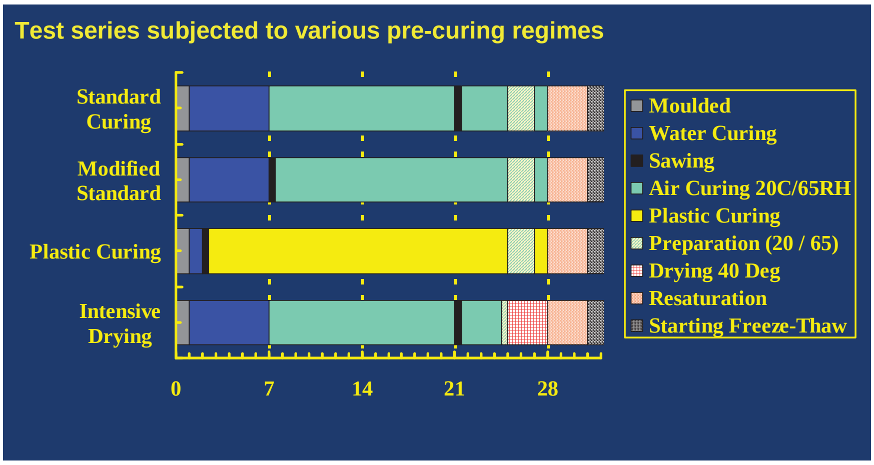
A key issue for Testing Performance - Moisture history, exposure & properties



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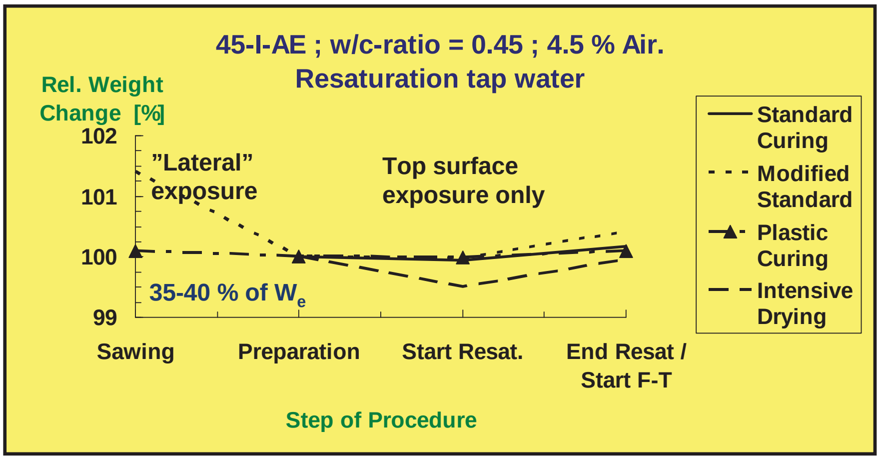
A key issue for Testing Performance - Moisture history, exposure & properties



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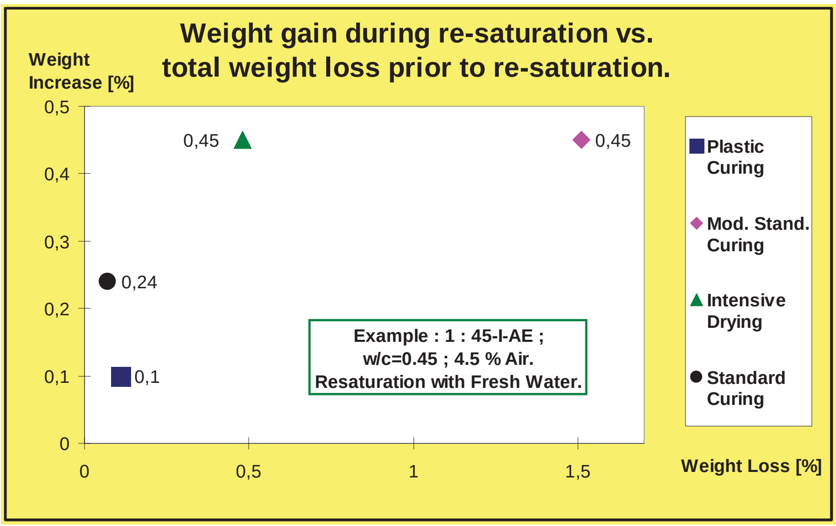
A key issue for Testing Performance - Moisture history, exposure & properties



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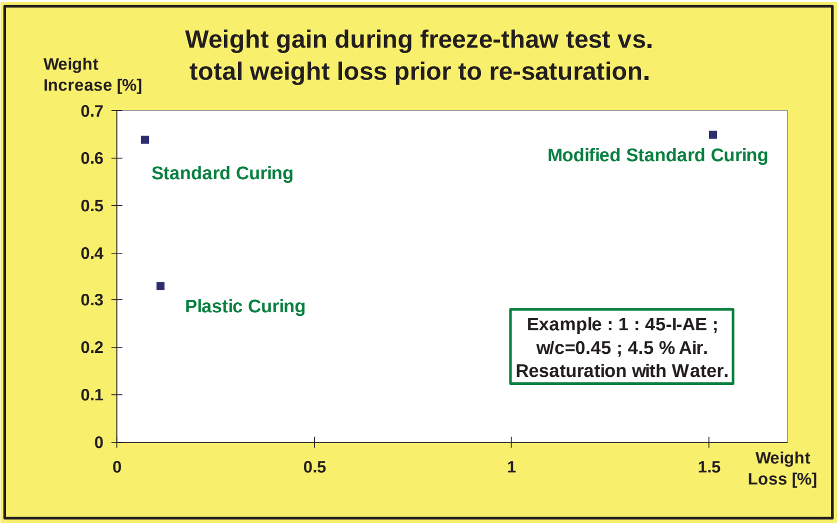
A key issue for Testing Performance - Moisture history, exposure & properties



Side 13 - 2012-02-16
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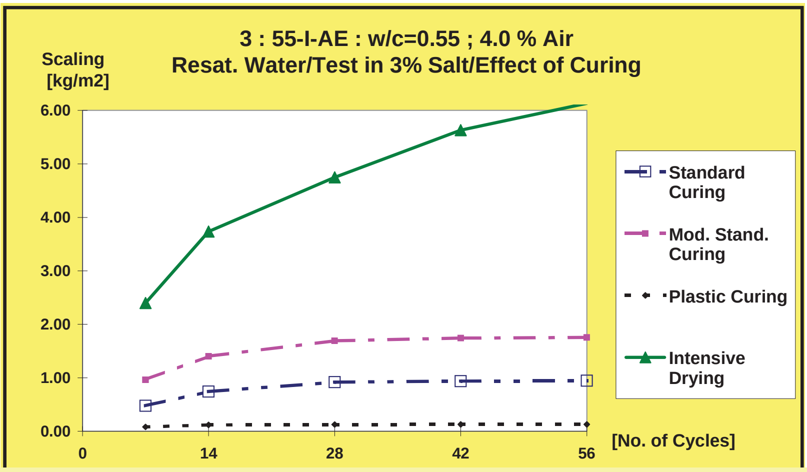
A key issue for Testing Performance - Moisture history, exposure & properties



Carbonation is considered positive to CEM I performance, implying that the plastic curing effect is attributed to the limited moisture exchange

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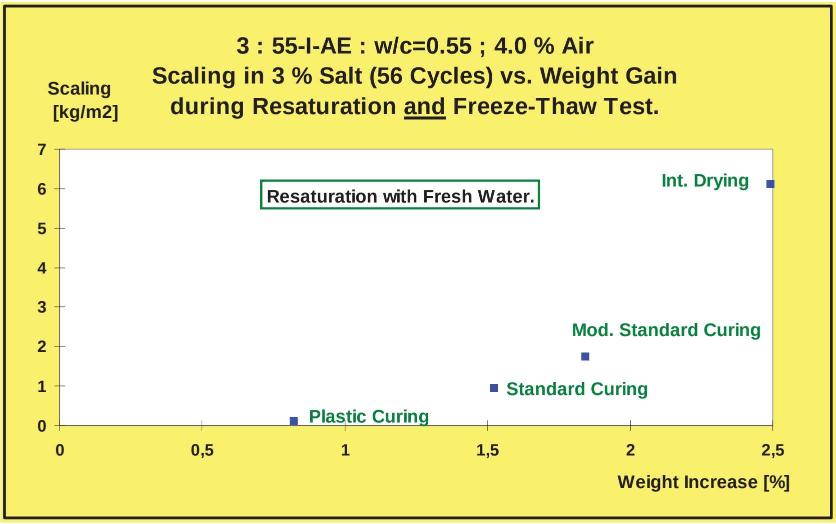
A key issue for Testing Performance - Moisture history, exposure & properties



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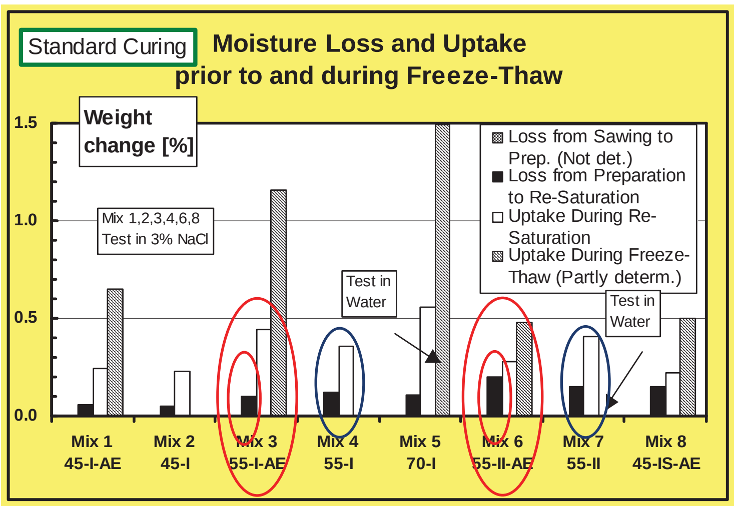
A key issue for Testing Performance - Moisture history, exposure & properties



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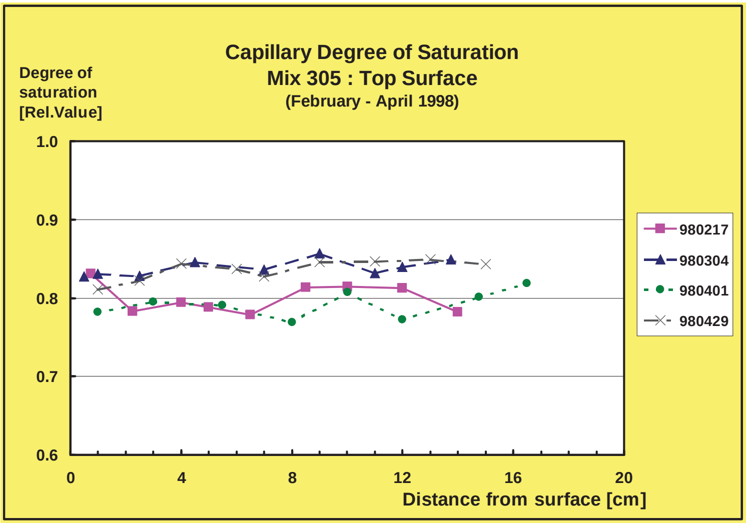
Degree of saturation in service …..?



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Conclusions

- Some modifications to the CEN/TS may be adopted now
- It essential to select the right measures
- The temperature cycle must NOT be changed
- Many countries miss the NA acceptance criteria (responsibility)
- The “bias” for XF 3 (non-saline) is not established
- The test methods are developed for “CEM I”
- The answer to prolonged pre-curing of slowly developing binders is not (automatically) prolonged water storage
- Research is needed to answer these requests

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Conclusions & Questions

- Reduced moisture exchange prior to F-T reduces scaling
- Reducing water storage/"curing" and replacing with plastic curing reduces moisture exchange
- Still : In both cases, S_{cap} prior to F-T is close to 100 %
- Long time (> 6h, 12h, 1d ?) water curing increases "$S_{cap\text{-}closed}$" ?
- S_{cap} during testing is beyond that of field conditions :
  - Initial saturation is higher
  - F-T pumping causes increased saturation

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L.o.i. .....

- ....
- ....
- ....

Side 20 - 2012-02-16
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Statens vegvesen
Norwegian Public Roads Administration

Low-heat concrete with fly-ash in massive infrastructures

Experiences from Norway on hardening phase crack sensitivity

Nordic Workshop, Oslo, February 15-16, 2012
Durability aspects of fly ash and slag in concrete

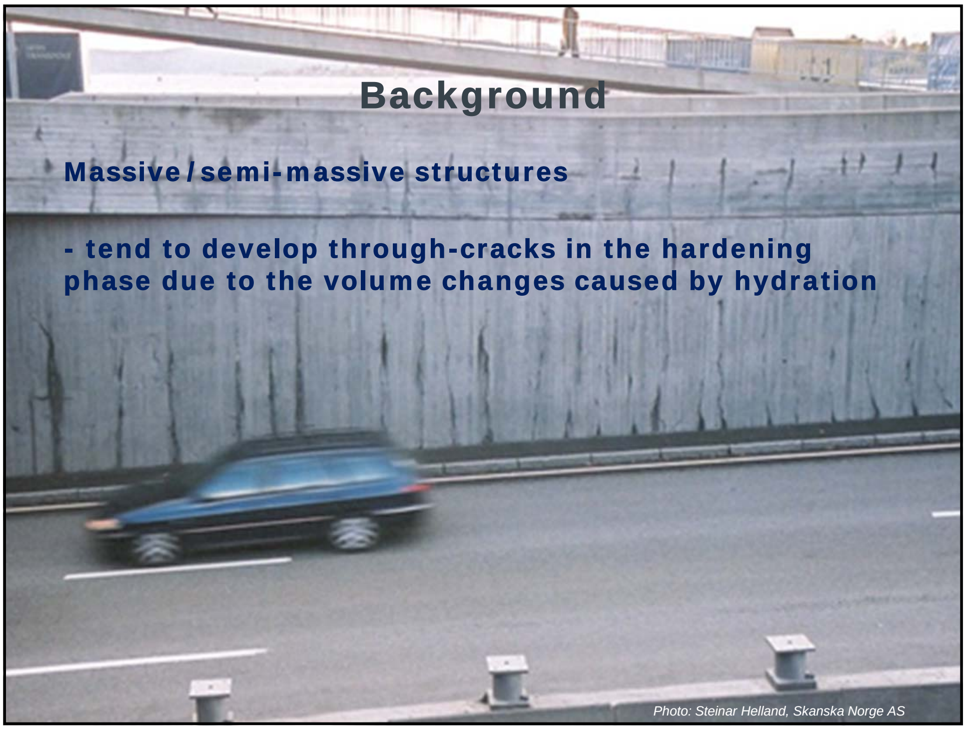
Øyvind Bjøntegaard
Norwegian Public Roads Administration (NPRA)
Tunnel and concrete division

vegvesen.no

Background

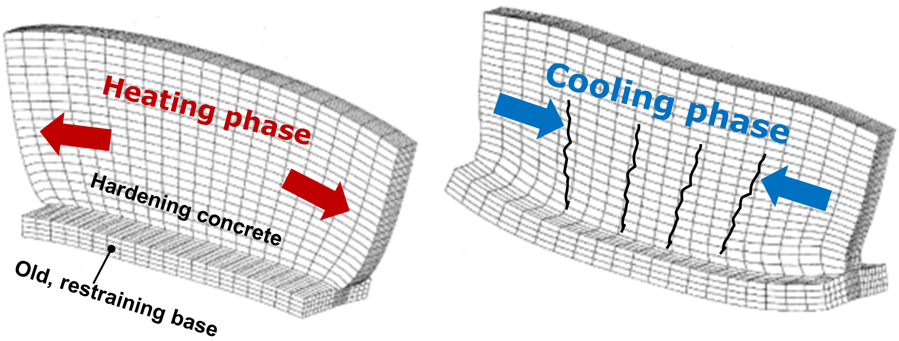
More and more underground infra-structures (urban areas)
- **ground water**
- **sea water**

The Bjørvika submerged tunnel system, Oslo



Background

Temperature is generally the main driving force, but autogenous shrinkage may also be significant



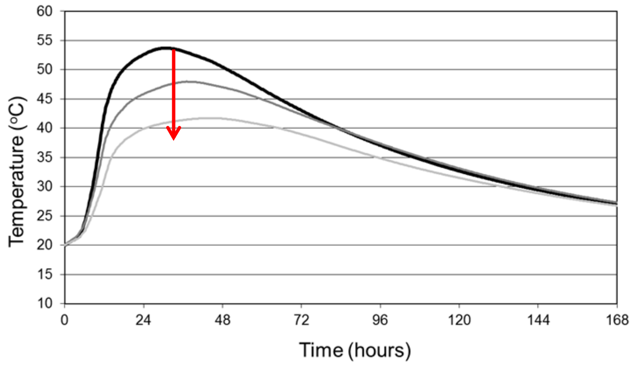
vegvesen.no

FEM-analyses, Jan Øverli, NTNU

Statens vegvesen
Norwegian Public Roads Administration

Background

Traditional strategy (used for a century):
Use a binder with low hydration heat to reduce maximum temperature / stresses / cracking tendency



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Heat is only one of many properties that determine the cracking tendency

- Thermal dilation
  - Temperature (**heat**, amount of binder, heat capacity)
  - Coefficient of thermal expansion
- Autogenous shrinkage
- Activation energy
- E-modulus
- Creep
- Tensile strength

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Norwegian Public Roads Administration

The onset of «high volume fly-ash» concrete in Norway

For our traditional CEM I-based SV-30/SV-40 concretes quite extensive cracking is sadly often the case in massive structures

Possible alternative concrete specifications were investigated by NPRA before the Bjørvika submerged tunnel project

- **2001-2004: NPRA's pre-documentation**
  - **fly-ash, slag and CEM III + CEM I-ref**
  - **durability parameters, strength, crack-risk**

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Norwegian Public Roads Administration

The onset of «high volume fly-ash» in Norway

- **2005-2011: The Bjørvika submerged tunnel project**

  Specifications (some of them):
  - **23-40% FA of binder (c + FA)**
  - 4-8% silica fume of c
  - w/(c+2s+0.7FA) ≤0.45
  - Full documentation of the early age properties for the chosen concrete mix(es)
  - Temperature- and stress simulations; C_i≤0.75
  - ***Result:***

    32-40% FA was used by the contractors, together with either cooling pipes or ice as part of mixing water

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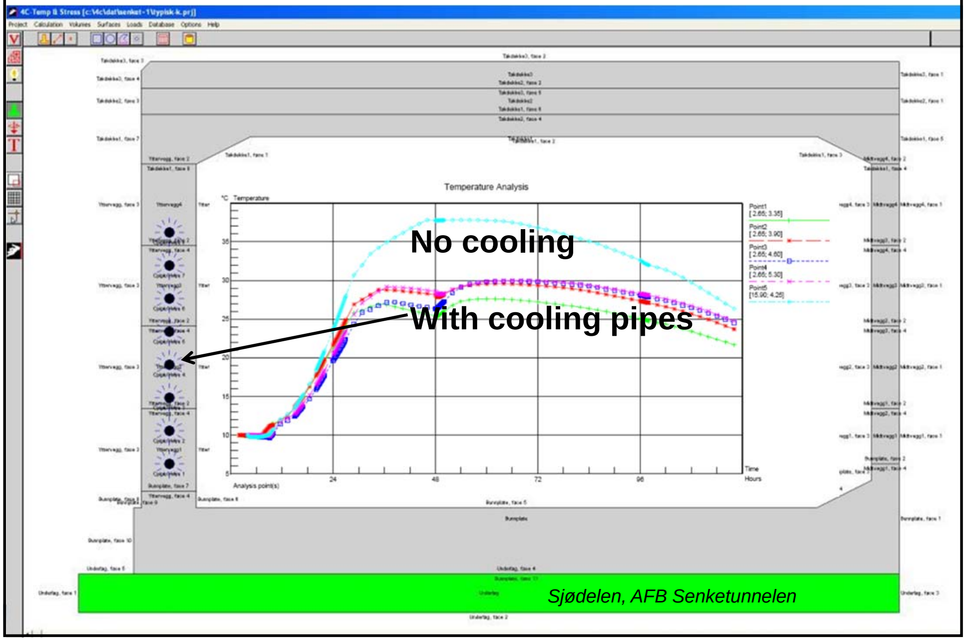
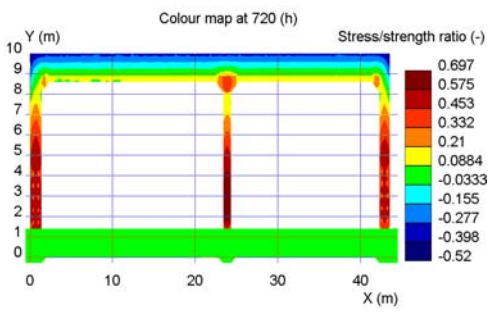
Simulations, cooling pipes



Using ice / simulations with low fresh concrete temperature



The simulations were decisive for the amount of cooling pipes or ice

AF Gruppen / Multiconsult

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Projects / structures

Project	Typical wall dimensions	Total fly-ash content in concrete	Extra counter-measures
Bjørvika: Havnelageret	1,0 m (var.)	40%	Cooling pipes
Bjørvika: Submerged tunnel	1,0 m	32%	Cooling pipes
Bjørvika: Sørenga	1,0 m	40%	Ice (low fresh concrete T)
NAV: Skansenløpet	0,8 m	32%	No
E6-øst Tr.heim: Møllenberg (to be build 2012-13)	1,0 m	?	Probably no

\+
\+ Bottom slabs: 1,0 – 1,3 m

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Experience

- **1.0 m wall thickness**
  - **32 % FA** and «normal restraint» condition (from 1 side): *Moderate cracking tendency* ⇒ **COOLING PIPES**
  - **40 % FA** and «high restraint» condition (from 2 sides): *Moderate cracking tendency* ⇒ **ICE as part of mix water**

  No cracks when these extra countermaeasures was used and worked as intended

- **0.8 m wall thickness**
  - **32 % FA** and «normal restraint»: No / very low cracking tendency

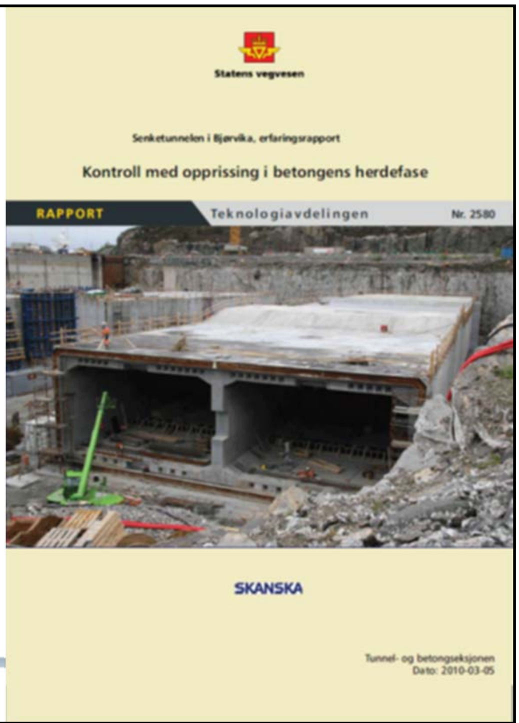
- Such good results not possible with our traditional concretes!

Experience

For the Bjørvika submerged tunnel:

Experiences with crack-control reported in 2010

(in Norwegian)



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To generalize is difficult / risky

The degree of restraint varies in different structural configurations

In addition to heat, autogenous shrinkage and tensile strength are also VERY important

The cracking tendency vary over the year

- Norwegian winter-conditions may be much worse than Norwegian summer-conditions

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Statens vegvesen
Norwegian Public Roads Administration

Normal heat
Semi low-heat
Low-heat

If a crack-free (massive) structure is strongly desired, the starting point for contractors will be that the **concrete mix** is the only «measure» to avoid cracking:

- **the composition and amount of binder**
- **aggregate type and grading /** D_{max}

Side-remark:

NS-EN 197-1 says a cement is «**low-heat**» if

$Q_{car,\ 7\ days} \leq 270$ kJ/**kg**

(The term low-heat is misused today, according to this term!)

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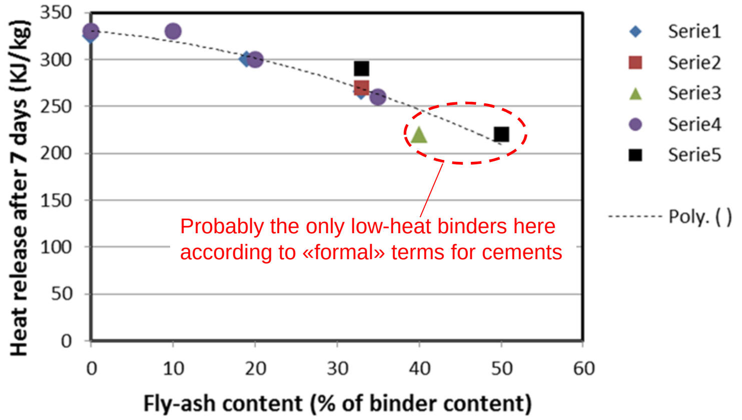
What is enough low-heat depends on the concrete mix / structure / situation



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Data from previous and present lab.- and infrastructure projects

Statens vegvesen

Variation in heat developoment during full-scale production

Data from the Bjørvika submerged tunnel project (32% FA)
1 m^3 semi-ad. calorimeters

Tabell 6. Målt varmeutvikling i sementen på Hanøytangen.

Herdekasseforsøk	Isoterm varmeutvikling ved 300 mh	Sement-batch
Hanøytangen 19.01.2006	270 kJ/kg	1. dokksetting
NTNU 03.05.2006	264 kJ/kg	1. dokksetting
Hanøytangen 28.09.2006	300 kJ/kg	2. dokksetting, ankommet 28/9, "fersk"
Hanøytangen 03.10.2006	320 kJ/kg	2. dokksetting, ankommet 28/9, "fersk"
Hanøytangen 13.11.2006	ca 290 kJ/kg	2. dokksetting, ankommet 28/9, "gammel"
Hanøytangen 30.11.2006	284 kJ/kg	2. dokksetting, ankommet 15/11, "fersk"
Hanøytangen 27.08.2007	288 kJ/kg	3. dokksetting, ankommet 20/8, "fersk"

Average: 288 kJ/kg

90% confidence interval: 257 – 319 kJ/kg

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Ref: Report 2010, Experience with crack control, Bjørviks submerged tunnel

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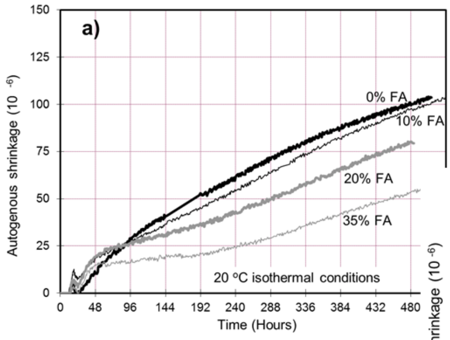
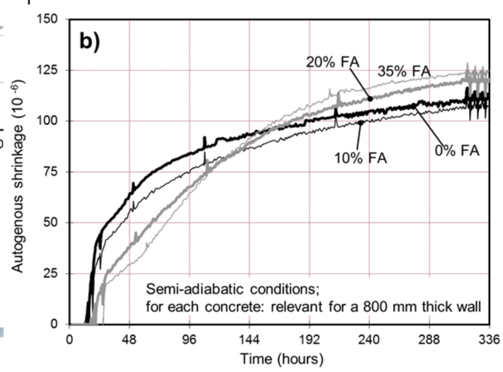
Norwegian Public Roads Administration

Autogenous shrinkage from isothermal and semi-adiabatic tests may be very different!



The relevant test condition is semi-adiabatic !! →



Ref: Upcoming COIN-report

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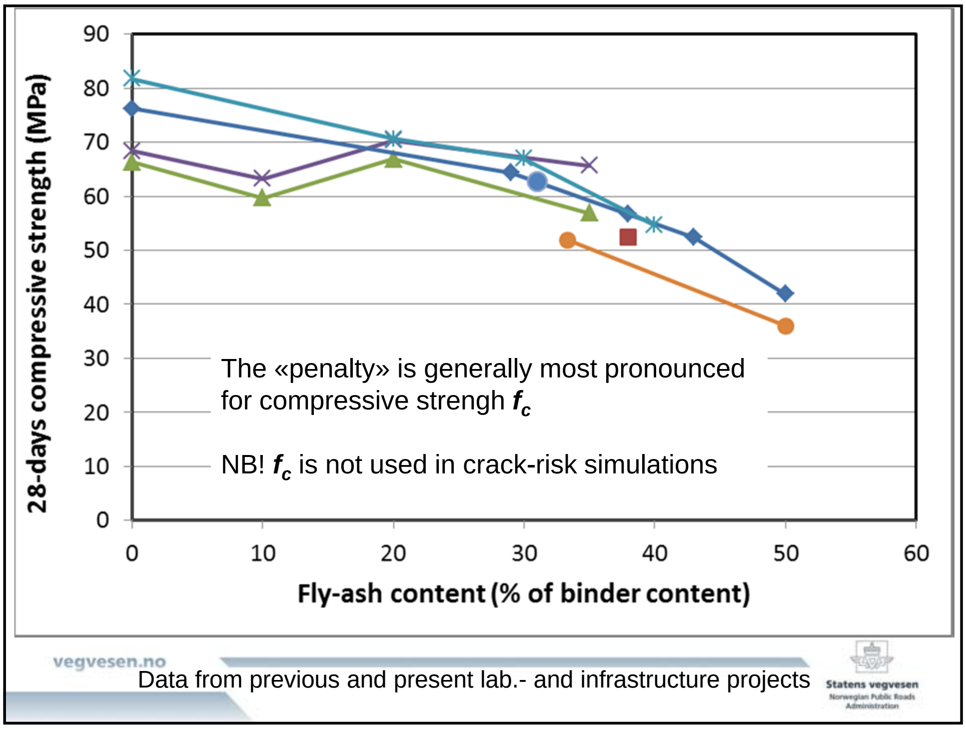
90
80
70
60
50
40
30
20
10
0
28-days compressive strength (MPa)
0
10
20
30
40
50
60
Fly-ash content (% of binder content)
The «penalty» is generally most pronounced for compressive strengh f_c
NB! f_c is not used in crack-risk simulations
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Data from previous and present lab.- and infrastructure projects
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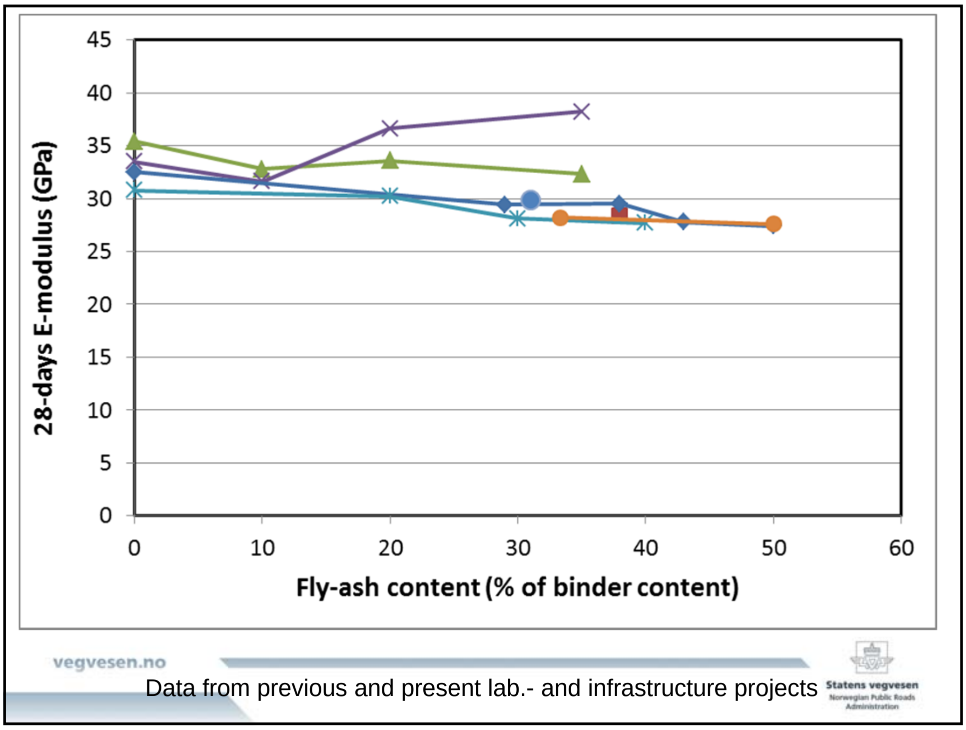
45
40
35
30
25
20
15
10
5
0
28-days E-modulus (GPa)
0
10
20
30
40
50
60
Fly-ash content (% of binder content)
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Data from previous and present lab.- and infrastructure projects
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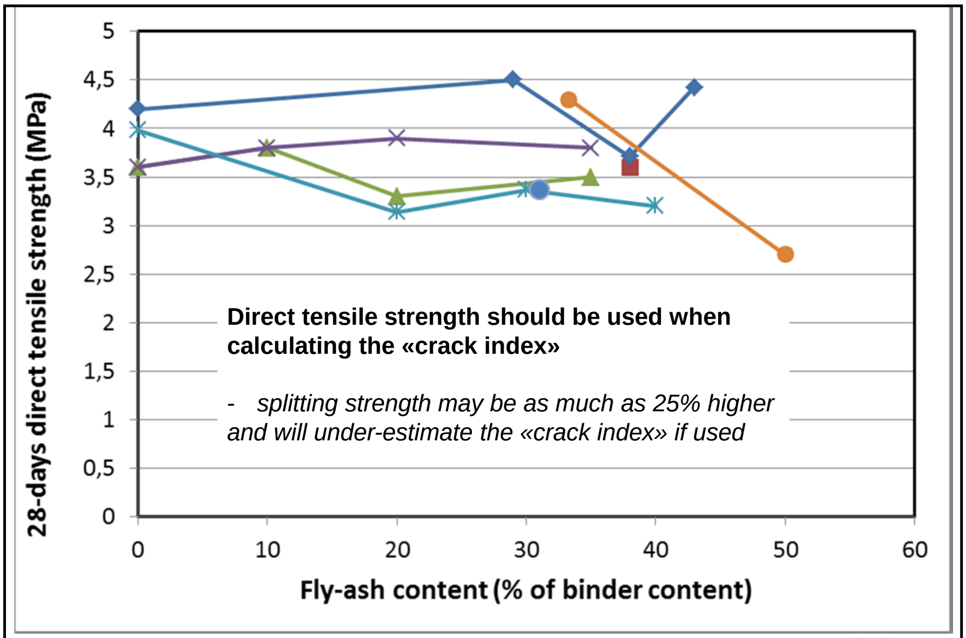

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Data from previous and present lab.- and infrastructure projects

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Final remarks
- experience, crack sensitivity

- **Heat (pr.kg) is systematically reduced with FA-dosage** for a given concrete mix
  - crack-free massive structures have been possible to make!
  - the results would have been different with trad. spec.
- **FA influences also the other properties**
  - Autogenous shrinkage (reduced at iso.cond, semi-ad?)
  - **Direct** tensile strength (secure significant results, and results at relevant maturity)
- Without extra countermasures **0.8-1.0 m thick wall structures** seem to require a «truly low-heat» concrete with a FA-content at least in the range 35-40% FA to become crack-free year-around (without extra countermeasures)
- Stress-simulations require time, costs and special competence
  - to be specified only in larger/special projects

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Final remarks

- Special concrete specifications also in the future for special projects
- **Adiabatic temperature rise** for a given concrete mix is a more relevant *quantity* than the heat release pr. kg binder

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Harald Justnes on

Self-healing potential in blended cements

RILEM TC221 on Self Healing:

Self Healing Concrete is a term that is used for cement-based materials that repair themselves after the material or structure gets damaged due to some sort of deterioration mechanism.

Usually the damage concerned is (micro)cracks enhancing degradations.

SINTEF SINTEF Building and Infrastructure 1

Self-healing in Portland cement concrete

- **Hydration of unreacted cement**
- Unreacted cement grains are encapsulated by a dense CSH-layer resulting in a slowed down continued hydration dominated by diffusion and water access.
- When a crack comes through or nearby, the hydration of the un-reacted cement grain will be revitalized due to increased access of water and wholly or partly close the crack by hydration products.

- **Carbonation**
- The binder contains a large amount of calcium hydroxide throughout. A crack will speed up the transport of CO_2 and speed up the carbonation process along the surface of the crack;
- $Ca(OH)_2$ (s) + CO_2 = $CaCO_3$ (s) + H_2O
- The volume increase of solid material in the above process is +12 vol%
- CSH will also carbonate resulting in CSH with lower C/S and $CaCO_3$

SINTEF SINTEF Building and Infrastructure 2

Self-healing ability of concrete based on blended cements

- **Two decreasing effects: dilution and pozzolanic reaction:**

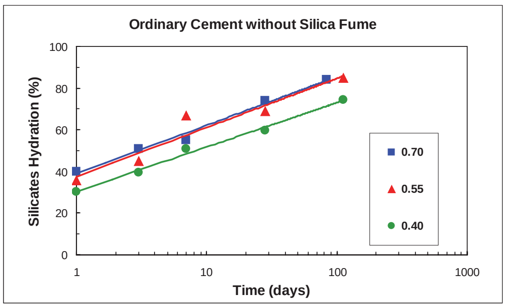
1. The **dilution** effect of cement resulting in less calcium hydroxide produced per volume unit of concrete
2. The **pozzolanic** reaction of the supplementary cementing materials consuming calcium hydroxide and also resulting in less calcium hydroxide per unit volume

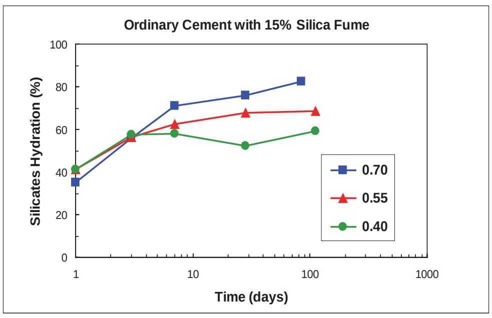
- Blast furnace slag is "latent hydraulic" and is believed not to consume much calcium hydroxide (if any) → 1st effect
- Fly ash is "pozzolanic" and consumes calcium hydroxide → 1st and 2nd effect

SINTEF SINTEF Building and Infrastructure 3

Unreacted cement by limited water access

1. Self-desiccation by low water-to-binder ratio and fast supplementary cementing materials (fly ash too slow to promote self-desiccation?)
2. Early drying

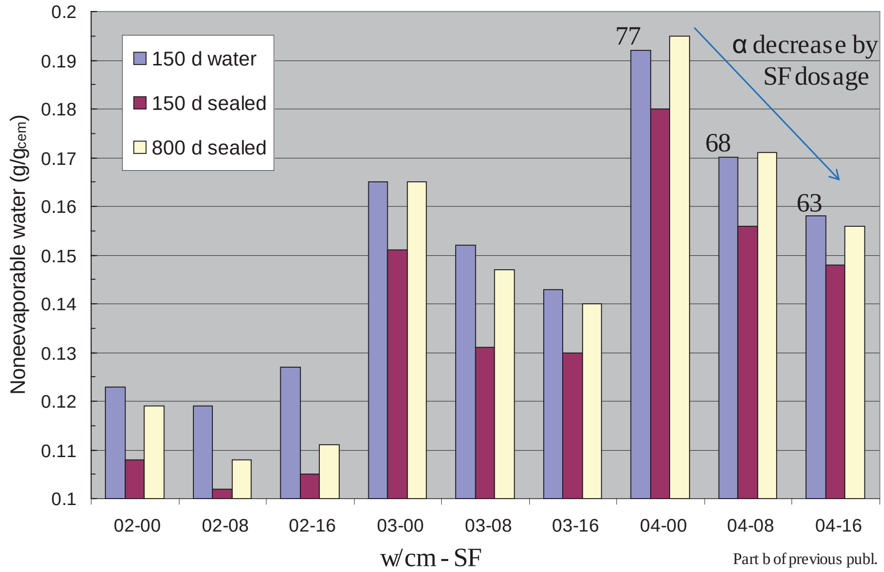




Justnes, H., Sellevold, E.J. and Lundevall, G.; "High Strength Concrete Binders. Part A: Reactivity and Composition of Cement Pastes with and without Condensed Silica Fume." 4th International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolana in Concrete, Istanbul, May 3-8, 1992, CANMET/ACI SP 132-47 (Volume 2) pp. 873-889.

SINTEF SINTEF Building and Infrastructure 4

Self-desiccation delaying hydration

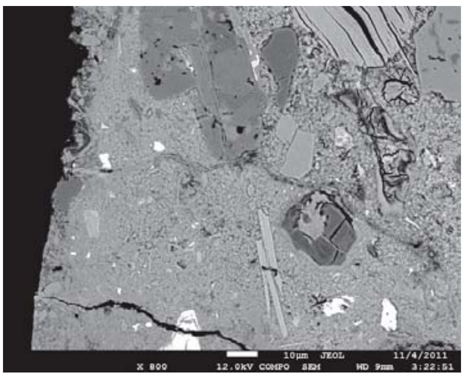


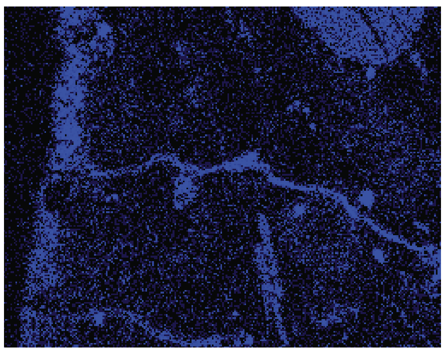
SINTEF

SINTEF Building and Infrastructure 5

Contact with sea water will improve self-healing of concrete

- Contains magnesium (1,350 ppm Mg^{2+}) that will precipitate as Brucite, $Mg(OH)_2$
- Saturated with calcium carbonate that will grow as Aragonite on concrete substrate
- Contains sulphates (2,655 ppm) that may form AFt/AFm with calcium aluminate hydrates





Courtesy of Klaartje De Weerdt and Mette R. Geiker

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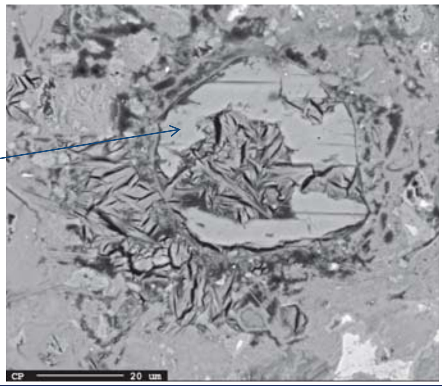
SINTEF Building and Infrastructure 6

Contact with sea water can improve self-healing of concrete

- Supplementary cementing materials containing aluminate produce much more calcium aluminate hydrates than Portland cement.
- Calcium carbonate can form calcium hemi- and mono-carboaluminate hydrates
- Sea water contains much more chlorides (1.9%) than the other species, so chlorides can form

Kuzel's salt ($Ca_3Al_2O_6 \cdot 0.5CaSO_4 \cdot 0.5CaCl_2 \cdot 10H_2O$)
or Friedel's salt ($Ca_3Al_2O_6 \cdot CaCl_2 \cdot 10H_2O$)



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SINTEF Building and Infrastructure 7

SCM and carbonation

- Not only CH carbonate but also CSH
- SCMs results in CSH with lower overall C/S ratio
- Low C/S type CSH will be less prone to carbonation in a crack

- However, alumina containing SCMs will form calcium aluminate hydrates
- How will they interact with carbonation?
- First one have to form calcium carbonate from CH and CSH
- And then as a secondary reaction voluminous calcium carboaluminate hydrates may form

SINTEF

SINTEF Building and Infrastructure 8

Calcium carbonate reacting with AFm to calcium mono-carboaluminate hydrate and AFt:

$2\,C\underline{C}$ +	$3\,C_4A\underline{S}H_{12}$ +	$18\,H = 2\,C_4A\underline{C}H_{11}$ +		$C_6A\underline{S}_3H_{32}$
m = 1.00 g	9.33	1.62	5.68	6.27
M = 100.09 g/mol	622.58	18.02	568.50	1255.26
n = 9.99 mmol	14.99	89.91	9.99	5.00
ρ = 2.67 g/ml	2.02	0.998	2.17	1.78
V = 0.375 ml	4.619	1.623	2.618	3.522

- The total increase in volume of solids can be calculated to
  ((2.618+3.522)-(4.619+0.375)·100vol%/(4.619+0.375) = **23 vol%**
- About **double** solid volume increase compared to carbonation of calcium hydroxide.

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Reaction of calcium carbonate with calcium aluminate hexahydrate to calcium mono-carboaluminate hydrate

- Calcium aluminate hexahydrate could be stabilized with alumina containing SCMs

$C\underline{C}$ +	C_3AH_6 +	$5\,H$ =	$C_4A\underline{C}H_{11}$
m = 1.00 g	3.78	0.90	5.68
M = 100.09 g/mol	378.29	18.02	568.50
n = 9.99 mmol	9.99	49.95	9.99
ρ = 2.67 g/ml	2.52	0.998	2.17
V = 0.375 ml	1.500	0.902	2.618

- The total increase in volume of solids is then
  (2.618-(0.375+1.500))·100vol%/(0.375+1.500) = **40 vol%**

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Increasing self-healing potential of concrete by

- Addition of micro, or even nano, "packages" that will be "activated" by cracks
- They can contain

1. Epoxy resin
2. Polyurethane
3. Water glass
4. Urea and bacteria using urease to form carbonate (2 separate packages)
5. Calcium lactate + bacteria; $Ca(C_3H_5O_2)_2 + 7O_2 = CaCO_3 + 5CO_2 + 5H_2O$

- My view, only 1 package of urea required as the following reaction will happen without bacteria; $O{=}C(NH_2)_2 + Ca(OH)_2 = CaCO_3 + 2\ NH_3$

- Involved in writing an EU-proposal called "INFRAHEAL" for the 2nd stage

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How to measure the self-healing potential????

- Induce cracks
- Measure self-healing by

1. Re-gaining the stress at the point of formation of the first crack
2. Re-gaining ultra-sound velocity
3. Re-gaining dynamic E-modulus?
4. Re-gaining permeability/diffusivity resistance
5. Etc

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Summary effect of blended cement on self-healing

- The dilution of cement ↓
- The pozzolanic activity decreasing CH ↓
- Self-desiccation by low w/b and fast SCM ↑
- Pozzolanic reaction producing calcium aluminate hydrates ↑
- Contact with sea water ↑

Thirty Five Years Experience with Slag Cement Concrete in Canada

R. DOUG HOOTON
UNIVERSITY OF TORONTO
DEPARTMENT OF CIVIL ENGINEERING

Slag in Canada

- Canada's steel industry is located in Ontario.
- Lafarge opened the first granulated slag grinding plant in 1976 near Hamilton Ontario.
- Within a few years, other cement companies started buying slag granules and separately grinding them at cement plants. All major cement suppliers in Ontario have slag available.
- Since ~1982, almost all concrete in Southern Ontario (ie ~10 Million people from Detroit to Toronto to Ottawa). Silica fume is also used for high strength and durability—and always together with slag.
- Some slag is shipped from US into Eastern Canada and into Vancouver.

Other SCMs in Canada

- Fly ash was used in Ontario from 1950s to 2008 but all coal-fired power plants will be closed by 2014.
- Fly Ash is still used in East Coast of Canada and in Western Canada
- Silica Fume production in largely in Quebec and in US near Niagara Falls. Silica fume is readily available from Ontario to the East Coast, and in the Vancouver area in the West.

Typical Slag Use in Different Applications

- All slag is added separately at concrete plants.
- 25% slag replacement of cement is used in almost all concrete, including high-strength and high-durability concretes containing silica fume.
- For sulfate resistance and ASR mitigation, 35-60% slag is used with high-C3A portland cements instead of sulfate resistant or low-alkali portland cements.
- For mass concrete, 50-80% slag has been used with high-C3A cements instead of low-heat cement.
- 90% slag binders have been used in cemented paste mine backfills.

CSA Portland Limestone Cement (15% limestone) Demo Project: PC+25% Slag vs PLC+25% Slag

PLC had 11.5% limestone

Equal Properties:
Strength Development (35MPa @ 28days)

Drying Shrinkage (<0.04% at 28d)

Coulombs (<1500 at 56 days)

Freeze/Thaw

Scaling Resistance

Nov. 2009 Barrier Wall

2009 Barrier Wall	PC +25% SLAG	PLC + 25% SLAG
Shrinkage (28d)	**0.038%**	**0.038%**
Strength (MPa)		
1	**9.5**	**10.3**
3	**19.3**	**19.4**
7	**25.6**	**26.8**
28	**36.9**	**37.9**
56	**38.9**	**38.0**
91	**40.7**	**40.2**
Freeze/Thaw Durability	**94%**	**94%**
MTO LS-412 Salt Scaling	**0.24 kg/m^2**	**0.24 kg/m^2**
RCP (Coulombs)		
28 days	**2070**	**1490**
56 days	**1930**	**1340**

Strengths of Air-entrained Concretes cured at 23 °C with limestone and SCMs

Mix Identification (all 400 kg/m3 mixes)	% clinker in binder	w/cm	Compressive Strength (MPa)			
			7 day	28 day	56 day	182 day
GU Cement Control	90*	0.40	39.3	45.5	50.7	52.6
GU + 40% Slag	53	0.40	32.8	46.2	49.2	51.2
GUL9 + 40% Slag	50	0.40	36.1	50.9	53.6	50.7
GUL9 + 50% Slag	41	0.40	34.6	49.0	53.0	51.0
GUL15 + 40% Slag	46	0.40	37.1	52.3	57.5	59.2
GUL15 + 50% Slag	38	0.40	36.3	55.3	60.1	65.6
GUL15+ 6% Silica Fume + 25% Slag	53	0.40	46.0	65.0	70.1	76.0

* 3.5% limestone and 7% gypsum

U. of Toronto Field site data

Permeability Index of Air-entrained Concretes cured at 23 °C with limestone and SCMs

Mix Identification (all 400 kg/m^3 mixes)	% clinker in binder	w/cm	Rapid Chloride Permeability ASTM C1202 (Coulombs)		
			28 day	56 day	182 day
GU Cement Control	90	0.40	2384	2042	1192
GU + 40% Slag	53	0.40	800	766	510
PLC 9% + 40% Slag	50	0.40	867	693	499
PLC 9% + 50% Slag	41	0.40	625	553	419
PLC 15% + 40% Slag	46	0.40	749	581	441
PLC 15% + 50% Slag	38	0.40	525	438	347
PLC 15% + 6% Silica Fume + 25% Slag	53	0.40	357	296	300

CSA A23.1 limit is 1500 coulombs @ 56d for C-1 Exposure

Durable Concrete

- Durable concrete can be made for most aggressive exposures provided appropriate materials, mix designs, and construction practices are followed.
- **Slag cement will improve the durability of concrete**, but as with any cementing material, it cannot guarantee durability if it is not used in good quality concrete or if concrete is poorly placed and cured.
- Durable concrete will have a **longer service life** and therefore be **more sustainable**.

Effect of Slag on Permeability and Chloride Penetration Resistance

Effect of Slag on Concrete (=[W] and w/cm)

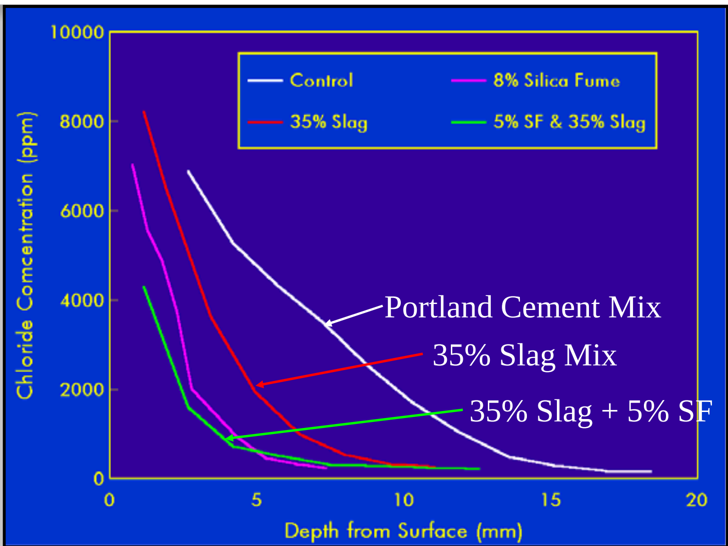
Slag %	Water	W/CM	91-day Strength MPa (psi)	RCPT (coulombs)	Permeability H_2O 10^{-13} m/s
0	200	0.45	35.8 (5190)	5200	10.1
25	200	0.45	42.7 (6190)	2450	5.4
50	200	0.45	42.8 (6200)	1020	2.3

5.1x

4.4x

R. Bin Ahmad & Hooton, 1991

Picton Concrete Pavements at 2 years: (ASTM C1556 Results)



Bleszynski, Hooton, Thomas, 2001

EFFECTS OF SLAG ON CHLORIDE DIFFUSION

CSA A23.1 Class C-1 Concretes: w/cm = 0.40

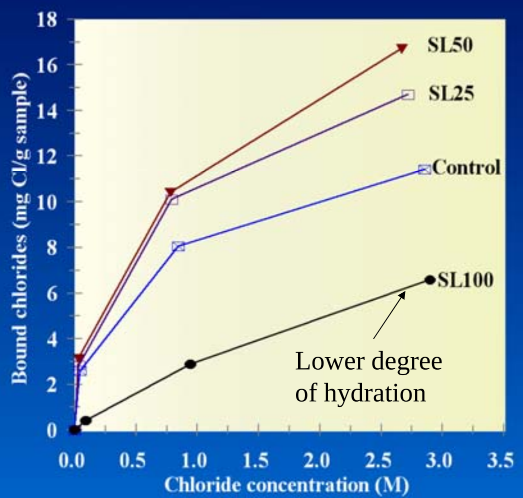
(Tests started at 56 days of age, 5 days moist cured)

	120 Day Ponding Test*	Migration Test
Type 10 PC	19.0 x 10^{-12} m^2/s	7.6 x 10^{-12} m^2/s
	3.8x	3.0x
25% Slag	5.0 x 10^{-12} m^2/s	2.5 x 10^{-12} m^2/s

** At 56 days of age 5 M NaCl Ponded at 40°C for 120 days.*

McGrath and Hooton, 1997

Effect of Slag on Chloride Binding



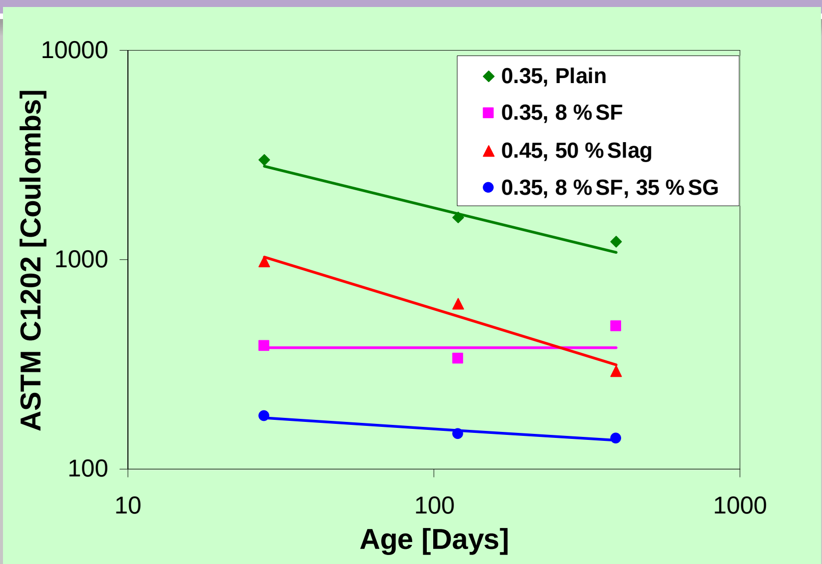
- Optimum GGBFS replacement level.
- Beside alumina content, C/A, C/S have influence.

Zibara 2001 (also CCR 2012)

Age-Dependant Changes in Chloride Diffusion Values

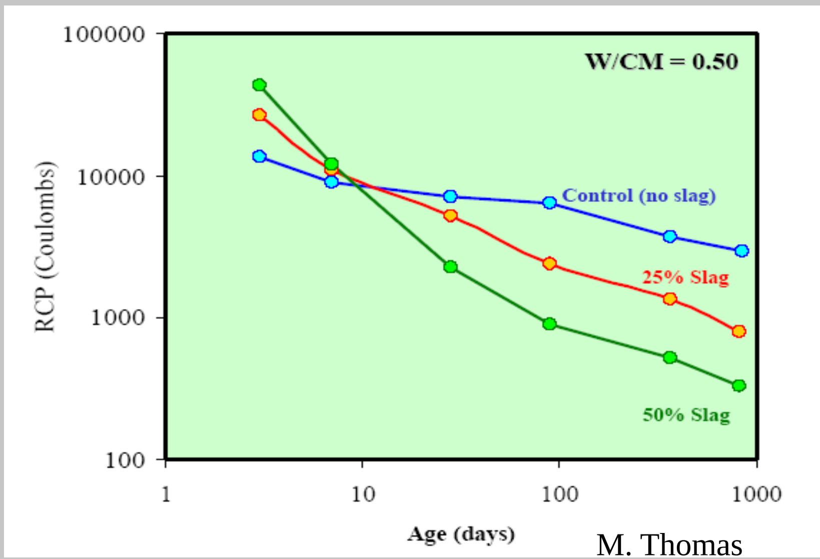
- In general, chloride diffusion coefficients will reduce as concrete matures.
- The magnitude of that change depends on the cementing materials and the initial curing achieved (slag and fly ash are very effective).
- This time-dependant reduction has a huge impact on service-life predictions and is recognized in Life-365 calculations.

Chloride Penetration Resistance - RCPT



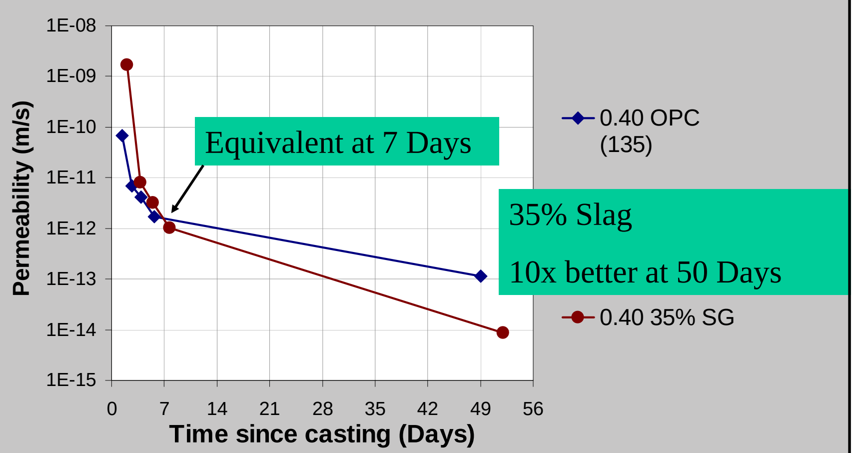
Stanish, Hooton and Thomas, 2000

Effect of Age on Coulombs



Early-Age Water Permeability Results

(calculated on inflow up to 7 days)



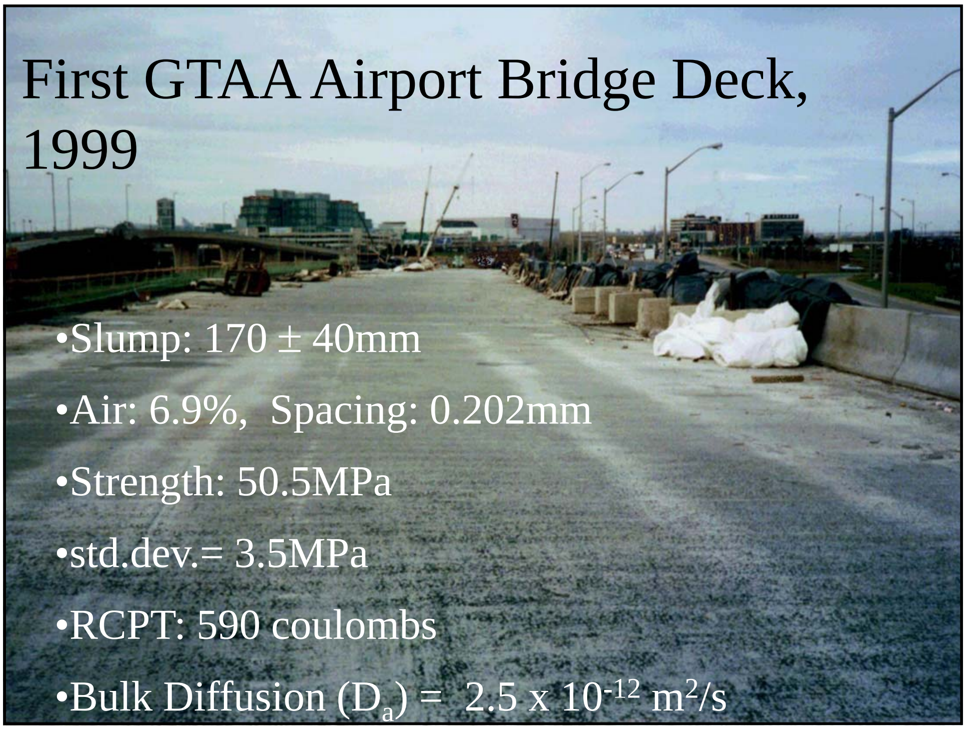
Nokken and Hooton, 2003

Slag-Silica Fume Ternary Mixes

- In Ontario, in almost every case where silica fume has been used since 1986, slag cement has also been used at 25-35% levels.
- Slag reduces stickiness and improves ease of finishing.
- Slag reduces the HRWR dose required.
- Slag reduces early heat of hydration.
- Slag continues to improve strength and chloride resistance beyond 28 days.

Bridge Decks at Toronto Airport

- In 1999, 4 bridge decks were placed using Type GUb-8SF blended cement + 25% Slag and 0.40 w/cm using the MTO High Performance Concrete Spec. but at 35MPa
- High corrosion resistance was required (<1000 coulombs).
- The concretes were placed in cold weather in 16h continuous placements of 1200m^3.
- Since then 70 bridge structures and terminal decks at the airport have used similar concrete mixtures.



TTC Fairview Parking Deck

- Multilevel level parking deck exposed to de-icing salts and freezing.
- **395kg/m³: Type GUb-8SF cement with 30% slag replacement.**
- W/CM = 0.37
- 45 MPa design, air-entrained.
- RCPT: **185 coulombs** (on cores at 60 days)
- Bulk Diffusion (D_a): **2.5×10^{-12} m²/s**
- Fog misting with car power washer helped prevent plastic cracks even on a sunny, 30°C+ day with a wind. Evaporation retarder also worked well.

Toronto Airport Parking Garage (8800 cars cap'y.)

- PT Decks
- Min.CM= 320kg/m3,
- 25% Slag, 0.40 W/CM
- 35MPa (+10L/m3 DCI on some decks)

Freeze/Thaw Resistance

Regardless of the cementing materials and admixtures used, concrete will be durable even if saturated when:

1. It is adequately air-entrained.
2. The aggregates are frost-resistant.
3. Adequate strength is developed before exposure to the first freeze (> 5 MPa) and cyclic freezing (> 20 MPa).


1994 Stoney Creek Slag Test Pavements
See Boyd & Hooton 2008 ASCE

June 1994 Field Trials

Six concrete mixtures were cast into pavement slabs which receive truck traffic and de-icing applications at Lafarge's Slag Plant in Stoney Creek.

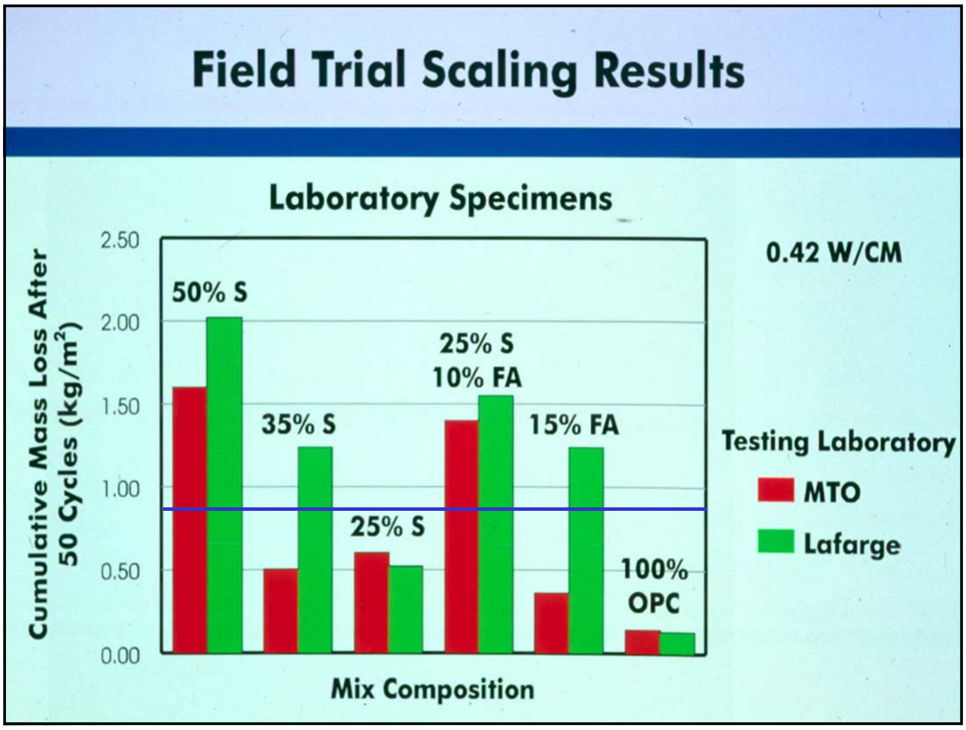
Variables:
- Cementing materials
- Curing: curing compound vs 4 days wet burlap and plastic
- Finishing time - early vs normal

Contacts:
- CM = 355 kg/m^3
- w/cm = 0.42

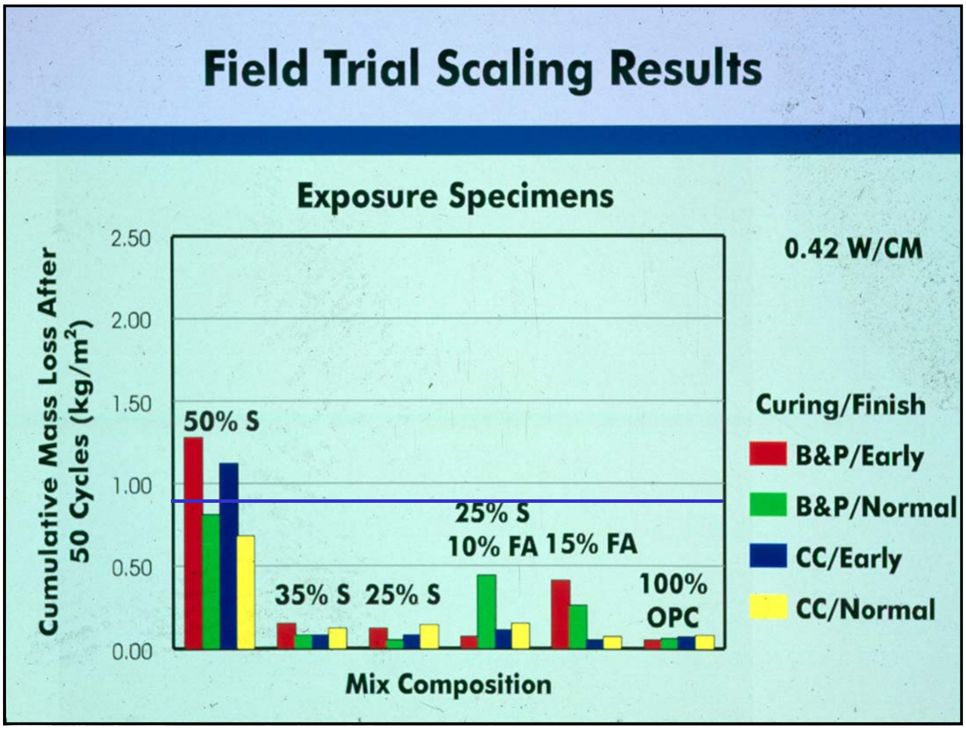
Tests:
- Field Performance
- Standard MTO LS412 Scaling Test at 28 days
- LS412 tests after 4 months field exposure
- Temperature monitoring of concrete slabs during winter

Standard Lab Scaling tends to show slag and fly ash concretes performing poorly

Lab. Test Slabs Were Finished and Cured The Same As The Pavements


Field Trial Scaling Results
Laboratory Specimens
0.42 W/CM
Cumulative Mass Loss After 50 Cycles (kg/m²)
2.50
2.00
1.50
1.00
0.50
0.00
50% S
35% S
25% S
25% S 10% FA
15% FA
100% OPC
Mix Composition
Testing Laboratory
MTO
Lafarge


Lab Test Slabs Left On Site for 4 Months Then Tested
Stoney Creek 1994


Field Trial Scaling Results
Exposure Specimens
0.42 W/CM
Cumulative Mass Loss After 50 Cycles (kg/m²)
2.50
2.00
1.50
1.00
0.50
0.00
50% S
35% S
25% S
25% S
10% FA
15% FA
100%
OPC
Mix Composition
Curing/Finish
B&P/Early
B&P/Normal
CC/Early
CC/Normal


CM 1 3 5 7
INCH 1 2 3
JUNE 1995
50% SLAG
Curing Compound
Early Finish
JUNE 1995
50% SLAG
Burlap & Plastic
Early Finish
JUNE 1995
50% SLAG
Curing Compound
Normal Finish
JUNE 1995
50% SLAG
Burlap & Plastic
Normal Finish
After 18 years, no further scaling has occurred

State DOT Specifications

SCA 2005

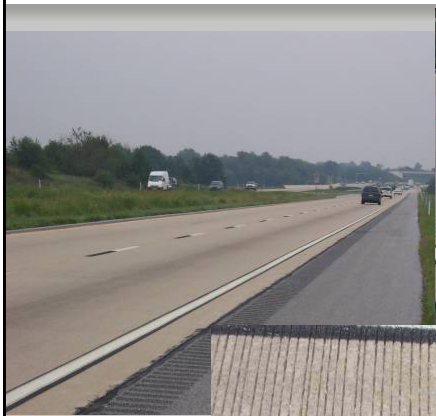
Pooled Fund Project TPF-5(100)

Deicer Scaling Resistance of Concrete Pavements, Bridge Decks, and Other Structures Containing Slag Cement

Performed by Iowa State University under Scott Schlorholtz with R. D. Hooton as co-PI.

- To document the field performance of existing concrete structures containing slag cement that have been exposed to cyclical freeze-thaw cycles in the presence of deicing chemicals

Delaware Route 1 SB
10 year old slag pavements, 35 and 50% slag



No scaling observed

Michigan 5 year old multilane, multispan bridge decks with 30% slag


No scaling observed

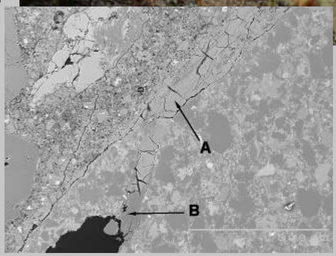
Field Scaling Noted

- Any field scaling noted to date appears to be due to:
  A) isolated areas where deep tyning of surface suggests the that the finishing was done too early,
  B) where inadequate air-entrainment was attained

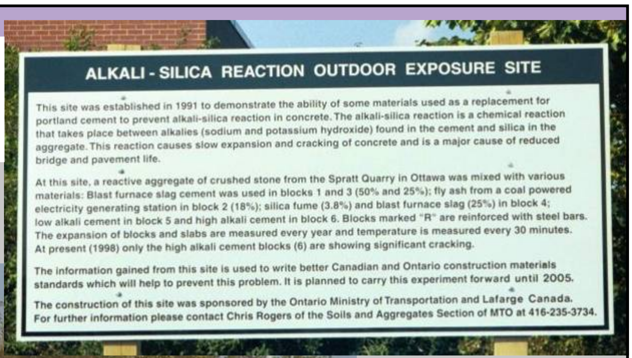
Also, Maryland DOT experience is that they never have scaling problems with their “A list” contractors.

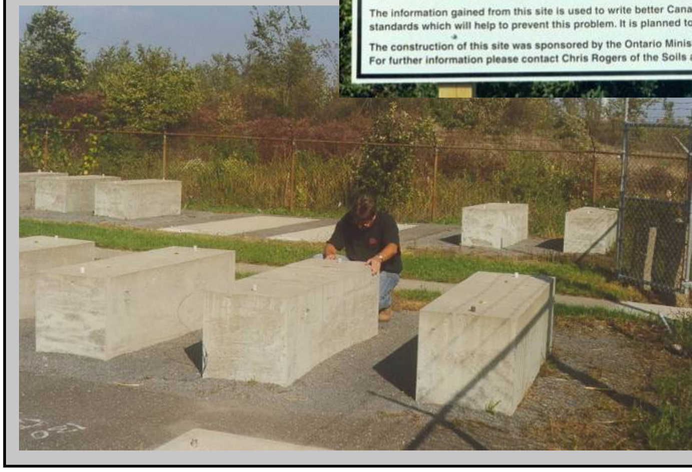
Alkali-Silica Reaction (ASR)

- ASR - a chemical reaction between the alkalis in portland cement and certain siliceous aggregates.
- Reactive silica in aggregates is attacked when exposed to the high-alkaline pore solution.
- Concrete cracks and swells, closing joints.

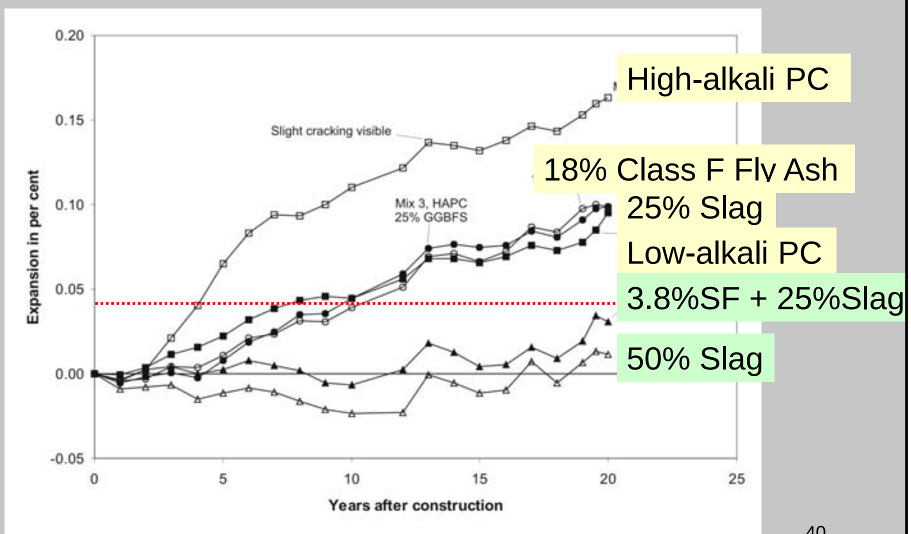


MTO Site Kingston, Ont.

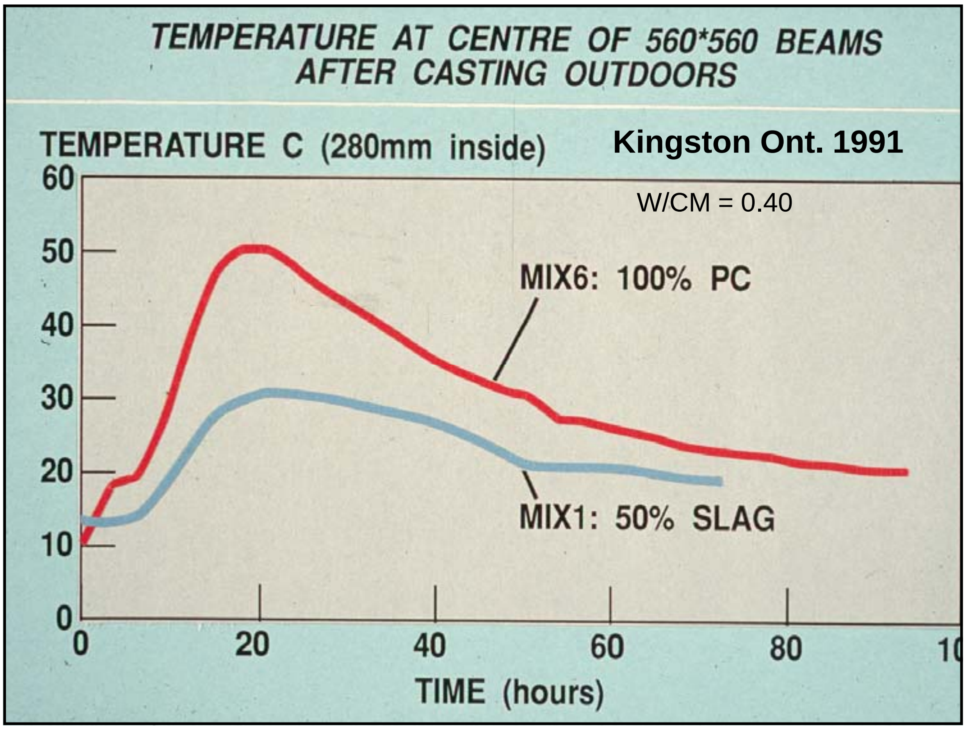




20-year Pavement Slab Expansions



40



Compressive Strengths (MPa) and Alkali Loading

Mix	50% Slag	18% F-Ash	25% Slag	25% slag +3.8%SF	LAPC	HAPC
w/cm	0.38	0.37	0.39	0.34	0.40	0.39
28 d	40.0	39.0	41.8	47.9	39.6	35.6
82 d	44.9	50.0	42.7	52.8	46.2	44.3
1y	49.7	52.4	50.9	63.2	54.9	49.2
7.25y	58.5	60.4	59.0	61.8	62.2	57.9
Alkali Loading (kg/m3)	1.64	2.67	2.46	2.34	1.91	3.28

Avg. # F/T cycles over 5 winters (from 1992/93 to 1996/97) and average temp. (January and July) at the site

	Average Number of Freezing Cycles					Average Temperatures	
Assumed Freezing Temp.	0°C (32°F)	-2°C (28°F)	-3°C (27°F)	-5°C (23°F)	-8°C (18°F)	January	July
Assumed Thawing Temp.	0°C (32°F)	0°C (32°F)	0°C (32°F)	0°C (32°F)	0°C (32°F)	°C (°F)	°C (°F)
Air (150 mm (6 in.)) above slab)	96	62	51	39	24	-6.2 (21)	23.9 (75)
Beam (50 mm (2 in.) depth)	65	46	42	30	21	-7.4 (19)	25.3 (78)
Beam (300 mm (12 in.) depth)	29	16	14	8	5	-6.1 (21)	24.8 (77)
Slab (50 mm (2 in.) depth)	47	26	25	12	6	-3.6 (26)	29.3 (85)
Slab (100 mm (4 in.) depth)	36	14	10	4	3	-3.0 (27)	28.7 (84)

Nokken, Hooton & Rogers ~2003

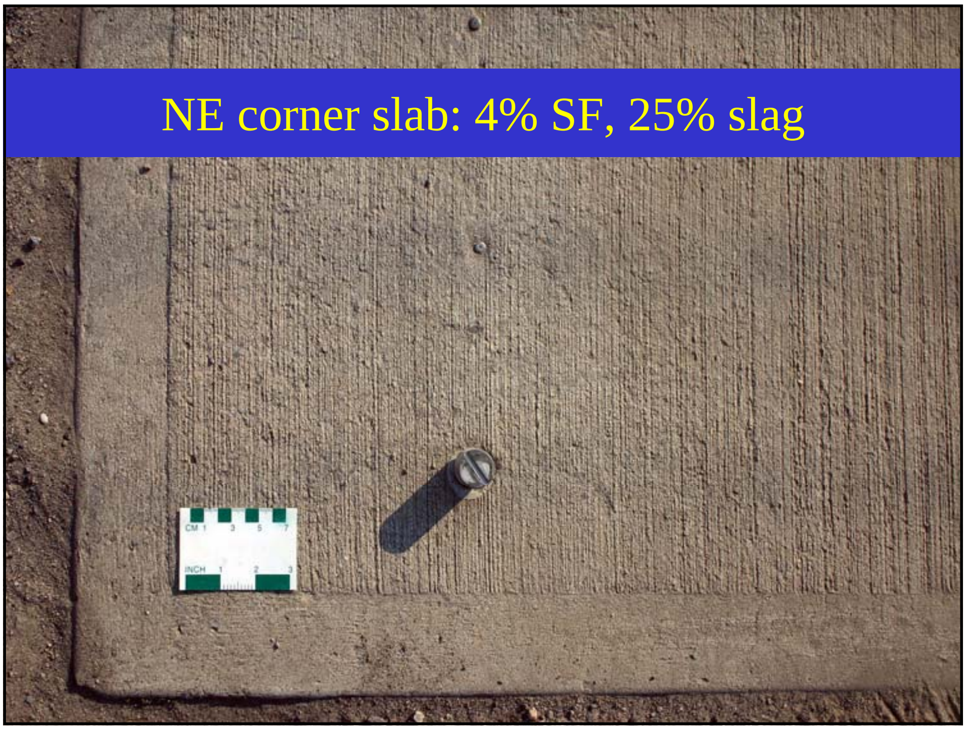
Chloride Penetration into slabs

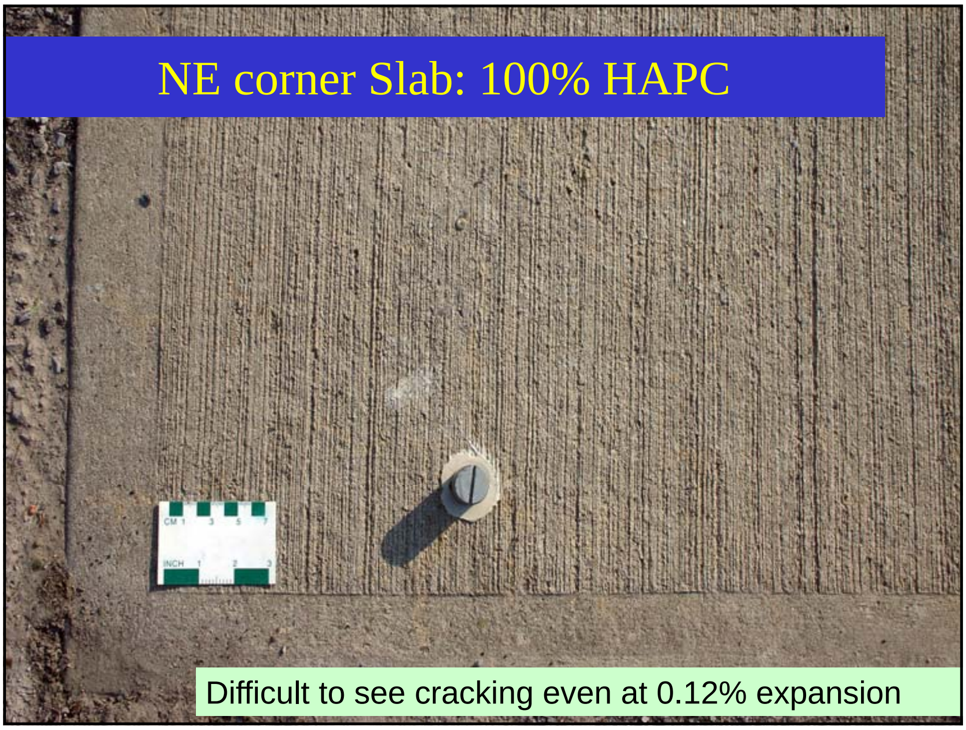
- Snow was cleared and the slabs were de-iced for the first 5 years Profiles were measured after 12 years.
- The average depth where chlorides had penetrated to a concentration of 0.05% by mass of concrete was 16.5mm (50% Slag), 19.5mm (18% FA), 17mm (25% Slag), 16mm (25% Slag+3.8% SF), 31.5mm (LAPC), and 29mm (HAPC).
- The Portland cement mixtures allowed chlorides to penetrate 50 to 100% further than the mixtures with SCMs.

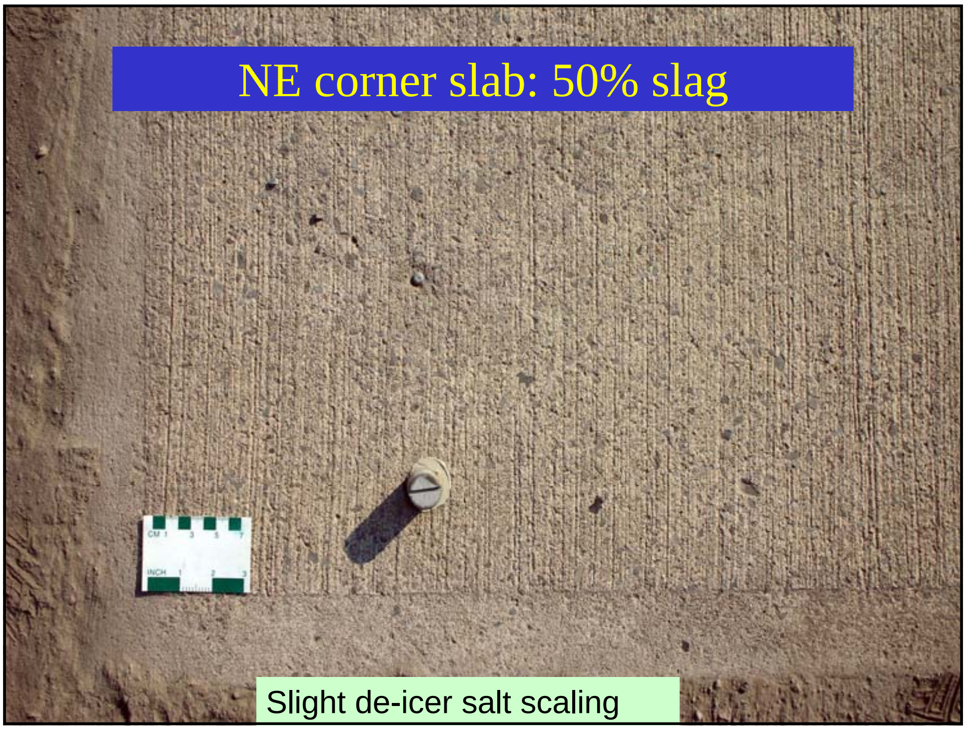
Chloride Bulk Diffusion (ASTM C1556) and ASTM C1202 data on 14-year cores from Slabs

	ASTM C1556 (42 Days Ponding)		ASTM C1202
Concrete Binder	Cs (mass %)	Da (10-12 m2/s)	(coulombs)
50% Slag	0.673	2.44	409
	0.622	2.24	245
18% Fly Ash	0.866	2.89	654
	0.687	7.5	541
25% Slag	0.977	3.94	1097
	0.774	5.4	851
25% Slag + 3.8% SF	0.728	1.74	212
	0.674	1.67	201
Low Alkali Cement	0.734	14.9	1901
	0.651	18.3	2161
High Alkali Cement	0.819	8.67	1826
	0.737	8.75	1509

NE corner Slab: 18% fly ash


NE corner slab: 4% SF, 25% slag


NE corner Slab: 100% HAPC
Difficult to see cracking even at 0.12% expansion

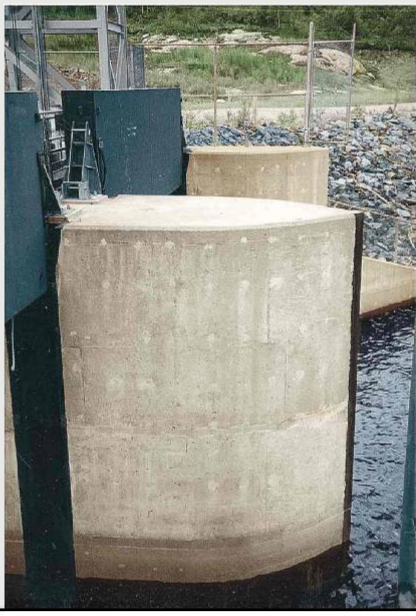

NE corner slab: 50% slag
CM 1 3 5 7
INCH 1 2 3
Slight de-icer salt scaling


Close up of Slab 1: 50% slag
Some Pop offs over some Coarse Aggregates but no scaling of mortar
CM 1 3 5 7

Steephill Falls Ontario: Spillway, Intake, and Powerhouse ASR Aggregate and 50% Slag Cement, 1988

Steephill Falls Spillway on Magpie River, Ontario

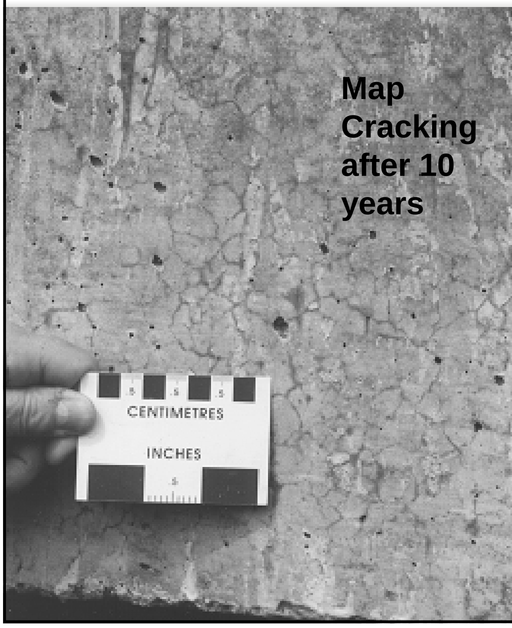
- *50% Slag Concrete made with ASR aggregate in 1988 is in excellent condition after 20 years.*
- *There was also no petrographic evidence of any ASR activity after 10 years.*
- *Note that Concrete was placed during the winter*

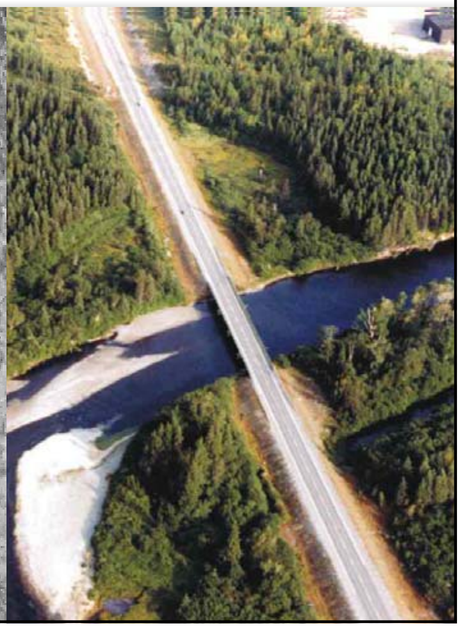


UNIVERSITY OF TORONTO
Department of Civil Engineering

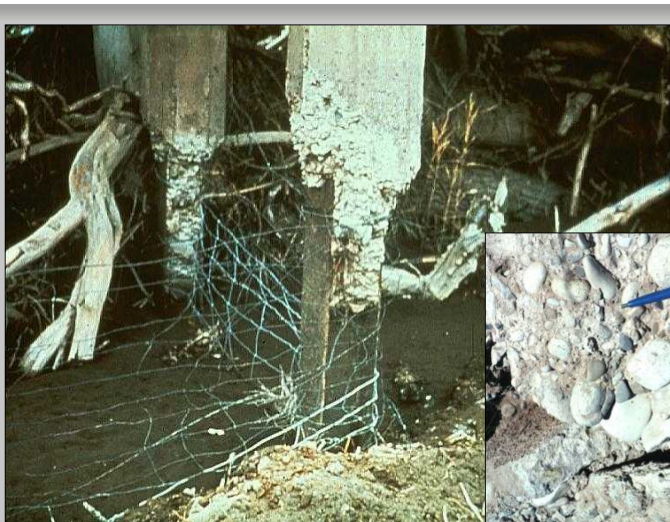
Magpie River Bridge on Highway 17, Cracked due to ASR

Built in 1989 with Portland cement and same aggregates as dam





Sulfate Resistance



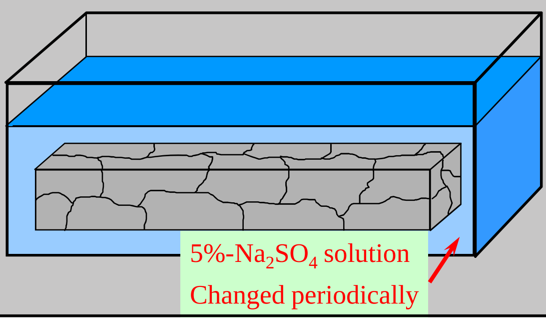
Bridge columns in North Dakota in sulfate soils

Sulfate Resistance

- 50% Slag has been allowed by Ontario Government agencies instead of Type V cement since 1983 for severe sulfate exposure.
- Silica fume can also work but the amount required exceeds the level typical in CSA Blended SF cements.
- Ternary SF Blended Cements +25% slag systems are effective.

ASTM C 1012- *Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution*

1. Aggregate/cementitious material = 2.75 & W/CM = 0.485
2. Mortars stored in limewater until a strength of 2850psi (20 MPa) is attained
3. Mortar bars (25 x 25 x 250 mm) then immersed in a 5% solution of sodium sulfate for 6 months or 1 year ~ length change monitored during storage



ASTM C989 Sulfate Expansion Limits
(ASTM C1012 Test)

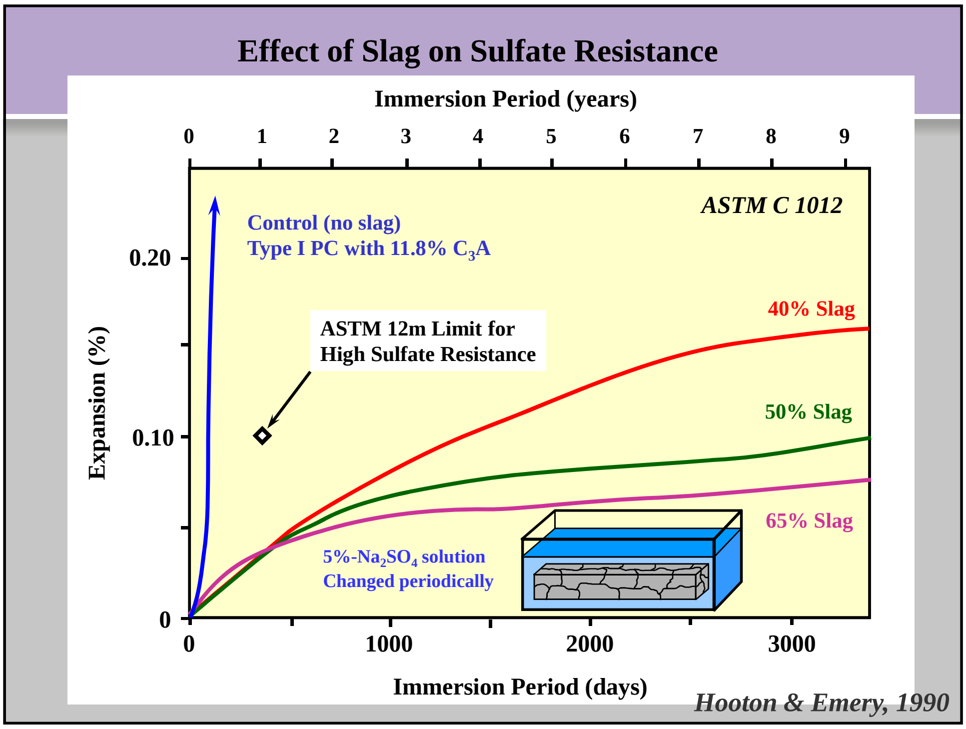
- Appendix (Non-mandatory)
  - Moderate exposure = 0.10% max. at 6 months
  - Severe exposure = 0.05% max. at 6 months
  - Similar limits are in ASTM C 595 and C 1157 Specifications for Blended Cements

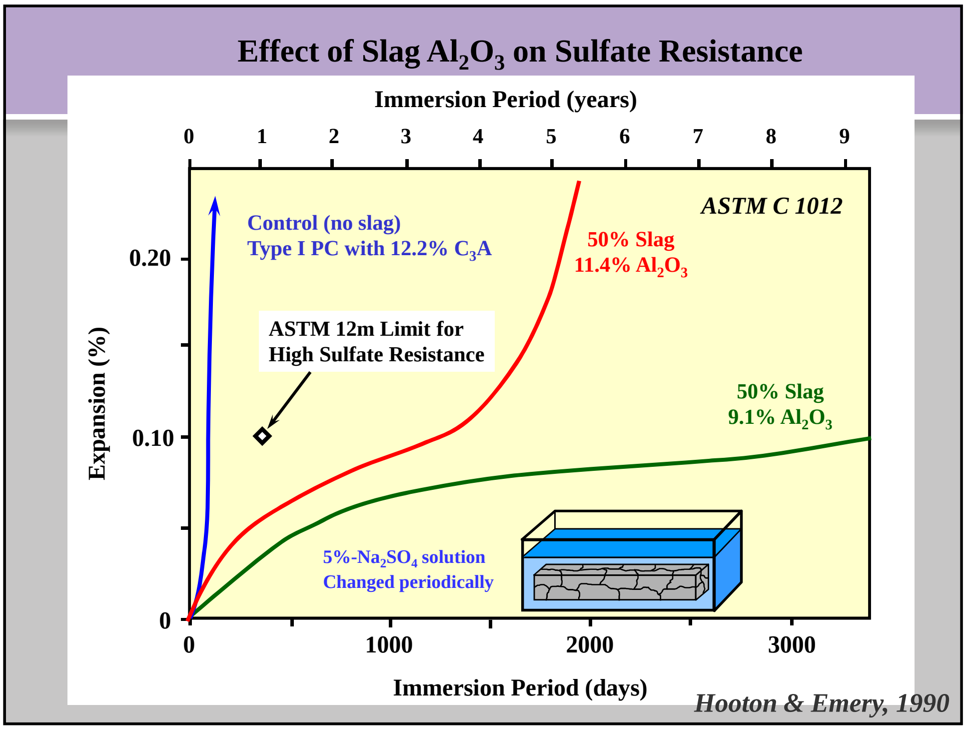
The ACI 318-08 Code uses the above limits plus 0.10% @ 18m for Very Severe exposure to allow combinations of cementitious materials to be used.

ACI C201.2R-01 Guide Requirements for Normal Weight Concrete Subject to External Sulfate Attack

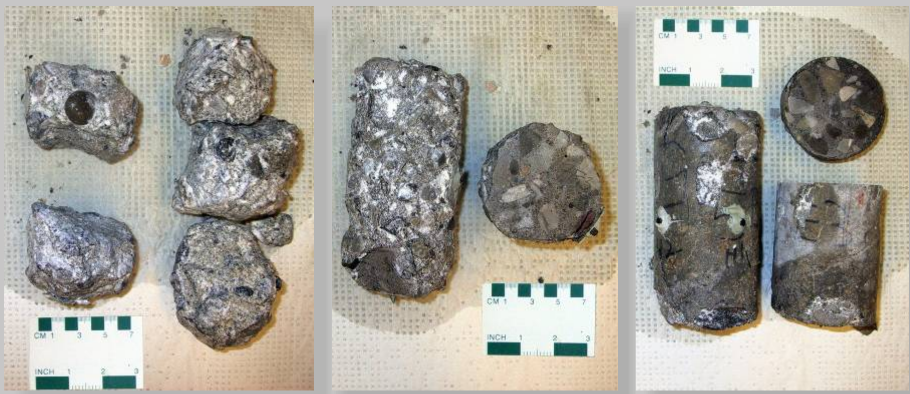
Exposure	Sol. Sulfate in Soil (% SO_4)	Sulfate in Water (% SO_4)	Cement	W/CM (maximum)
Mild Class 0	0.00 – 0.10	0 – 150	-	-
Moderate Class 1	>0.10 – 0.20	150 – 1500	Type II or Equiv.[1]	0.50
Severe Class 2	0.20 – <2.00	1500 – 10,000	Type V or Equiv. [2]	0.45
Very severe Class 3	Over 2.00	Over 10,000	Type V+ or HS + pozzolan or slag [3]	0.40

[1] Blend of any PC (C_3A> 7%) and slag or pozzolan tested by C 1012 at 12m to give equivalent sulfate resistance (<0.10%@12m); Type IS(MS);Type IP(MS); or Type MS.
[2] Blend of any PC (C_3A> 7%) and slag or pozzolan tested by C 1012 to give equivalent sulfate resistance (<0.05% @6m and <0.10%@12m); or C 1157 Type HS.
[3] or C 1157 Type HS +a pozzolan or slag tested by C 1012 to give < 0.10% @ 18m.


Effect of Slag on Sulfate Resistance
Immersion Period (years)
0 1 2 3 4 5 6 7 8 9
ASTM C 1012
Control (no slag)
Type I PC with 11.8% C_3A
0.20
40% Slag
ASTM 12m Limit for
High Sulfate Resistance
Expansion (%)
50% Slag
0.10
65% Slag
5%-Na_2SO_4 solution
Changed periodically
0
0 1000 2000 3000
Immersion Period (days)
Hooton & Emery, 1990


Effect of Slag Al_2O_3 on Sulfate Resistance
Immersion Period (years)
0 1 2 3 4 5 6 7 8 9
ASTM C 1012
Control (no slag)
Type I PC with 12.2% C_3A
50% Slag
11.4% Al_2O_3
0.20
ASTM 12m Limit for
High Sulfate Resistance
Expansion (%)
50% Slag
9.1% Al_2O_3
0.10
5%-Na_2SO_4 solution
Changed periodically
0
0 1000 2000 3000
Immersion Period (days)
Hooton & Emery, 1990

Concrete: Effect of C_3A in Portland Cement
w/c =0.50, 21 years in 50,000 ppm $MgSO_4$

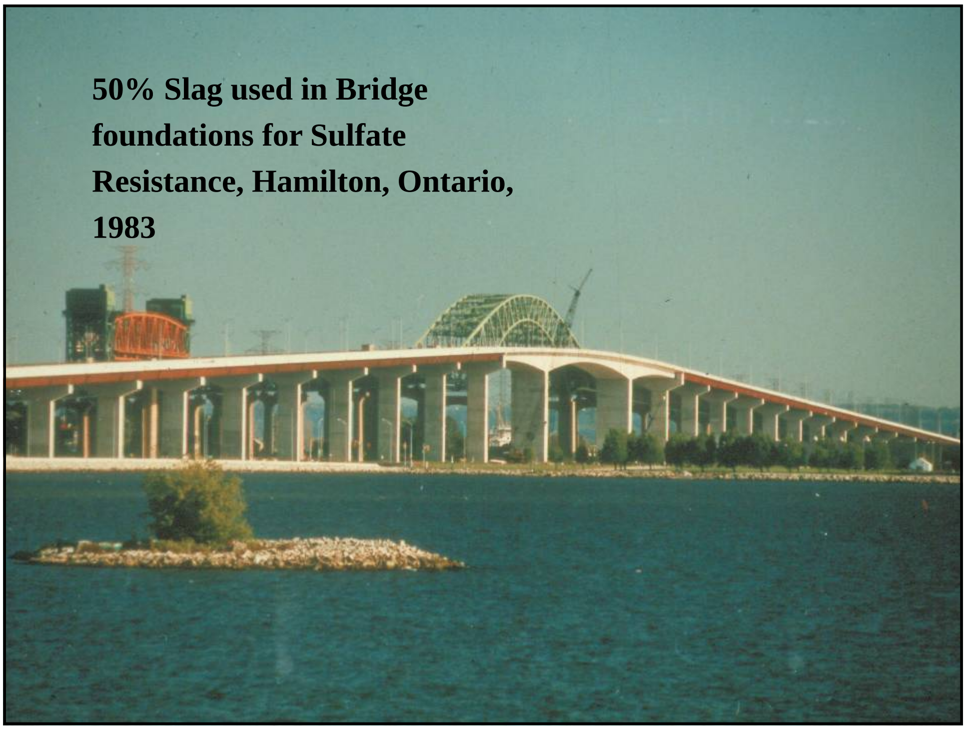


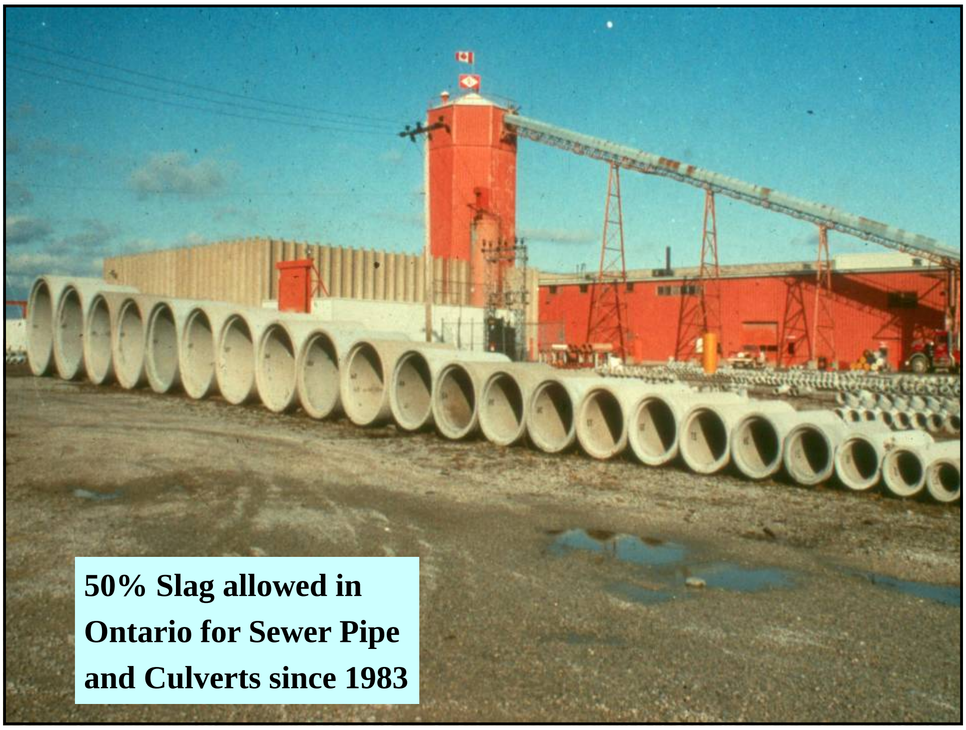
12.3 % C_3A **7.1 % C_3A** **3.5 % C_3A**

(Saw Cut cylinders on right side)

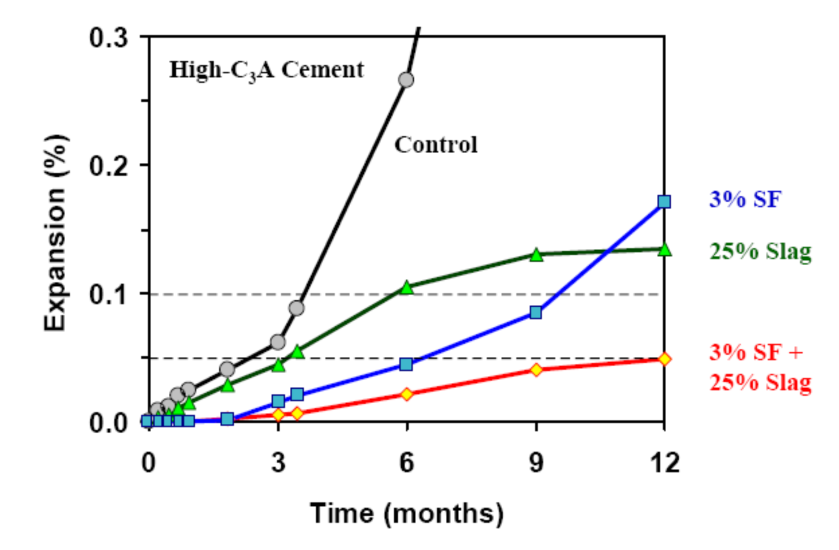
Hooton and Emery

Type I, 12.3% C_3A Cement + 72% Slag
w/c =0.50, $MgSO_4$ for 24 years


50% Slag used in Bridge
foundations for Sulfate
Resistance, Hamilton, Ontario,
1983


50% Slag allowed in
Ontario for Sewer Pipe
and Culverts since 1983

Slag + Silica Fume (ASTM C1012)



Some additional points

- In a severe sulfate environment, use of Type V cement or slag cement is no guarantee against sulfate attack.
- Regardless of what cementing materials are used, obtaining low permeability concrete is of prime importance.
- This is achieved through low W, low W/CM, and good curing. SCM's such as slag will also reduce permeability.

Drying Shrinkage

7 Days Moist Curing, then dried at 50% rh

0.38 W/CM, 350 kg/m^3 CM, 20 mm Agg.

Cement Type	7 days	28 days	56 days
Type I	0.026%	0.046%	0.052%
Type I + 25% Slag	0.020%	0.036%	0.042%

D. Wannamaker, 1996

Drying Shrinkage with ASTM Type I (CSA GU) Cement

7 Days Moist Curing, then dried at 50% rh

0.55 W/CM, 300 kg/m^3 CM, 20 mm Agg.

Cement Type	7 days	28 days	56 days	91 days
Type I	0.022%	0.032%	0.039%	0.044%
Type I + 25% Slag	0.012%	0.027%	0.035%	0.041%
Type I + 50% Slag	0.011%	0.018%	0.032%	0.035%

Hooton, 2006

Summary: Experience with Slag Durability

- Slag reduces permeability and chloride penetration of concrete.
- Slag reduces rate of steel corrosion in concrete.
- Slag can eliminate ASR expansion / damage.
- 35-50% Slag can provide Type V performance or better for sulfate resistance when used with Type I or II cements (Slags with Al_2O_3 >12 % may require higher % slag).
- At replacement levels of 40 + %, there is increased risk of de-icer salt scaling on pavements, sidewalks and curbs, especially with poor workmanship and curing.
- Drying shrinkage is less than or equal to PC mixes.

Ternary blends – experiences from laboratory and practice

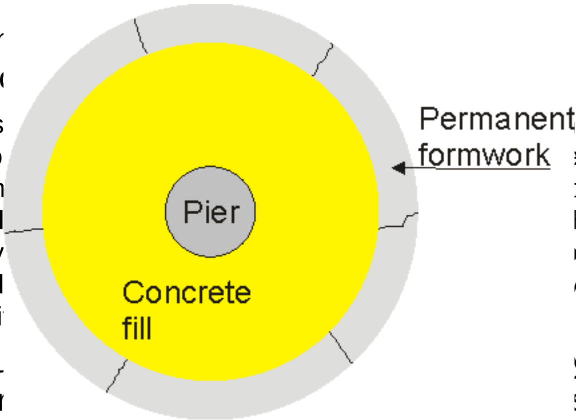
Per Fidjestol
Elkem AS Silicon Materials

Content

- Study on HAC at CCCC Wuhan Harbour Engineering Design and Research Institute Ltd.
- Some experiences with other SCM's
  - RHA
  - Milled Glass
  - Micronized Perlite
  - Superclassified fly ash

Wuhan – Background and goal of investigation

- In Chir … for some (
  - This … r. Burrows who … basis of a mon … d publ … hua, a very … ng due to inad … ated posi
- The pu … y crack risk for … strength and chloride resistance



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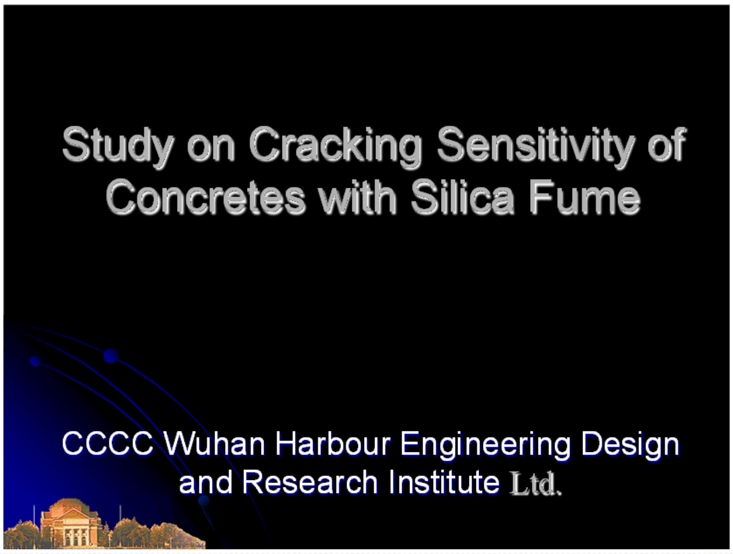
China – Cracking Issue



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Wuhan – concrete mixes

NO.	Code	C:F:S:M	W/B	Mixing proportion	FA%	MS%	SL%
1	0M0F0S-34	100:0:0:0	0.34	Ref concrete 1	0	0	0
2	4M0F0S-34	96:0:0:4	0.34	P II +4%MS	0	4	0
3	8M0F0S-38	92:0:0:8	0.38	P II +8%MS	0	8	0
4	12M0F0S-42	88:0:0:12	0.42	P II +12%MS	0	12	0
5	4M25F0S-34	71:25:0:4	0.34	P II +4%MS+25%FA	25	4	0
6	4M0F0S-38	96:0:0:4	0.38	P II +4%MS	25	4	0
7	0M25F0S-38	75:25:0:0	0.38	P II +25%FA	25	0	0
8	8M25F0S-42	67:25:0:8	0.42	P II +8%MS+25%FA	25	8	0
9	0M25F30S-34	45:25:30:0	0.34	P II +25%FA+30%GGBS	25	0	30
10	0M0F0S-38	100:0:0:0	0.38	Ref concrete 2	0	0	0
11	4M25F0S-38	71:25:0:4	0.38	P II +4%MS+25%FA	25	4	0
12	4M0F0S-42	96:0:0:4	0.42	P II +4%MS	0	4	0
13	8M0F0S-42	92:0:0:8	0.42	P II +8%MS	0	8	0
14	8M25F0S-34	67:25:0:8	0.34	P II +8%MS+25%FA	25	8	0
15	12M0F0S-38	88:0:0:12	0.38	P II +12%MS	0	12	0
16	8M25F0S-38	67:25:0:8	0.38	P II +8%MS+25%FA	25	8	0
17	4M25F0S-42	71:25:0:4	0.42	P II +4%MS+25%FA	25	4	0

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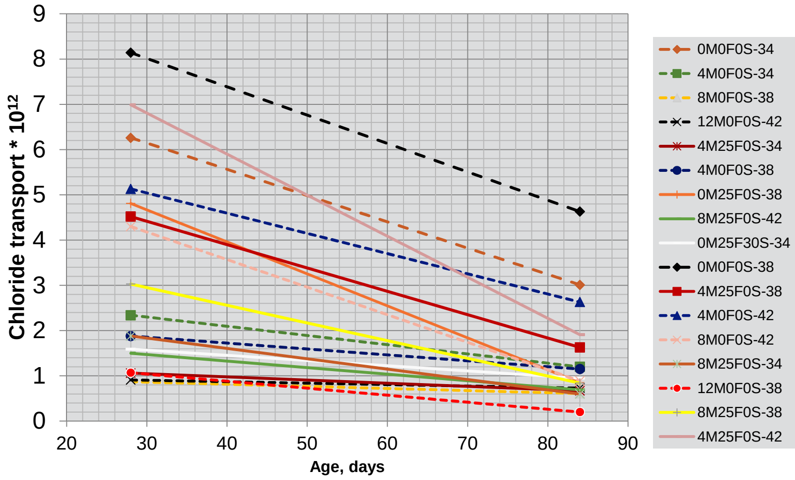
Chloride collection - migration



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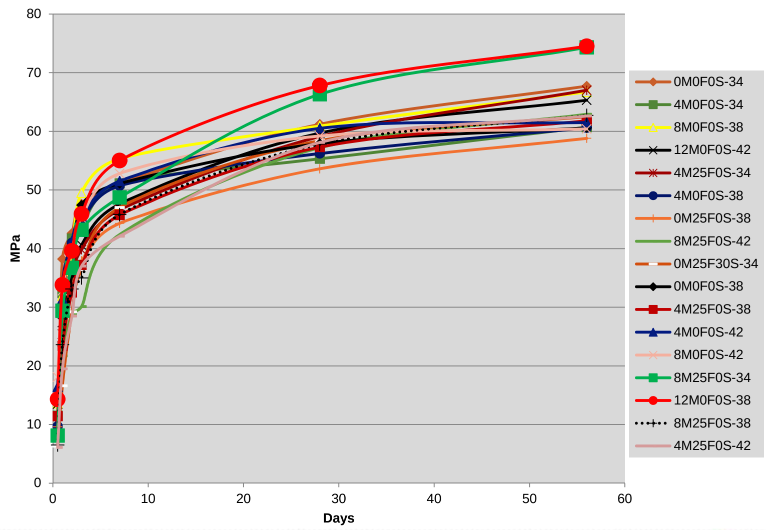
Compressive strengths



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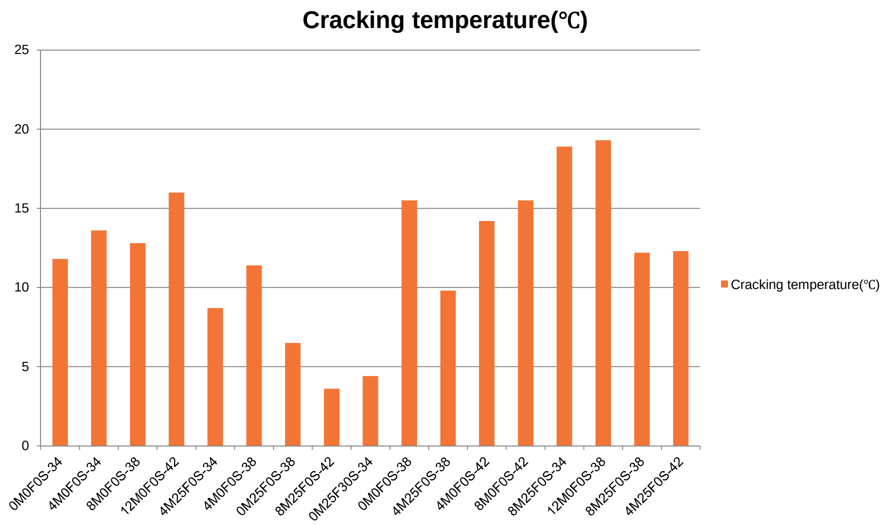
Cracking temperature



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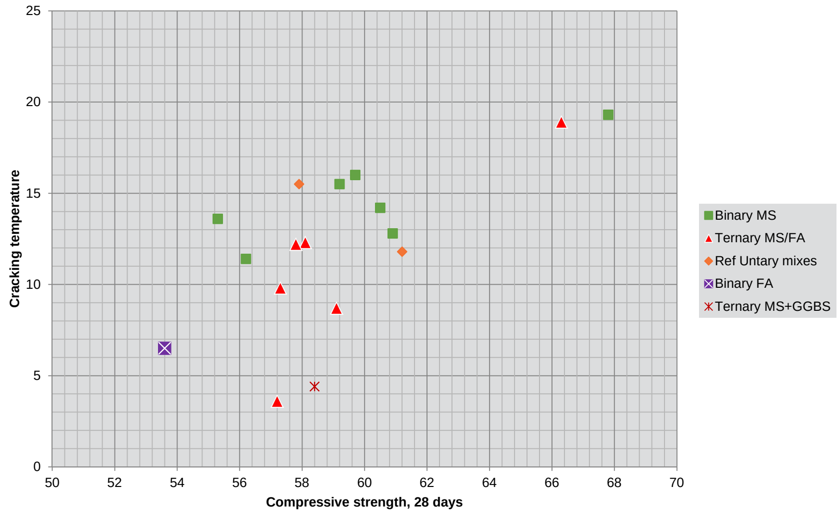
Strength versus cracking



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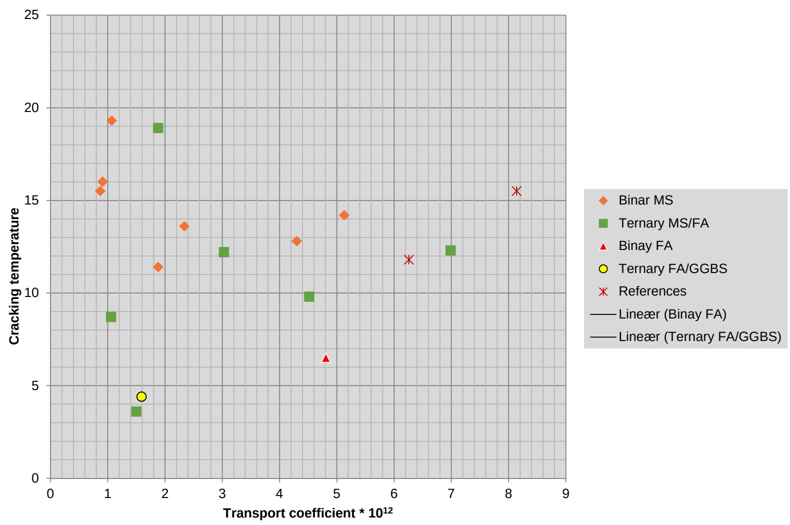
24 day Cl versus cracking temperature



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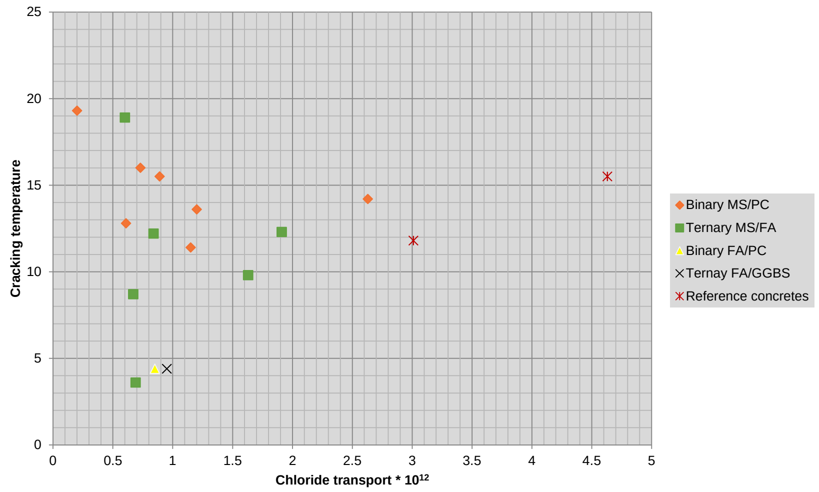
84 day Cl versus cracking temperature



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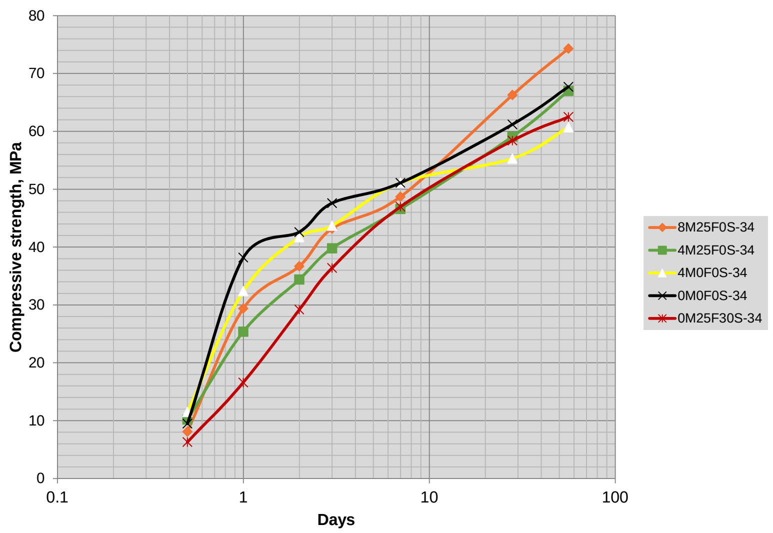
Compressive strength, selected mixes, w/cm=0.34



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Conclusions, Wuhan (from the Institute)

- A small amount of silica fume can greatly increase the permeability resistance, make up the shortcomings of low early strength of fly ash concrete and improve mechanical properties of concrete.
- Also other properties silica fume concrete can be better than that of the concrete with fly ash or slag powder, for high-strength concrete structures in marine environment with special need for durability.
- In all, silica fume has a broad application prospects in practical engineering.

Comments, Wuhan

- This was a very good GGBS
- Ternary blends work great, and crack risk can be minimized

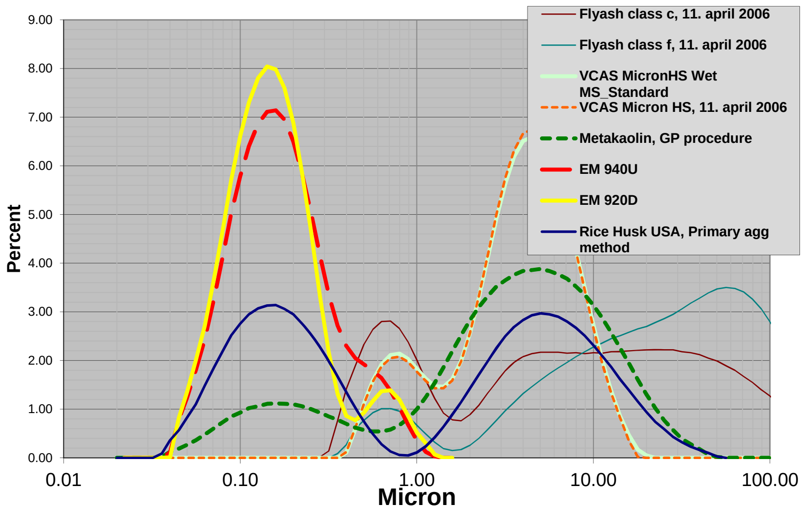
Some other experience

Other SCM's

Elkem
A Bluestar Company

15 09.07.2012

Other SCM's



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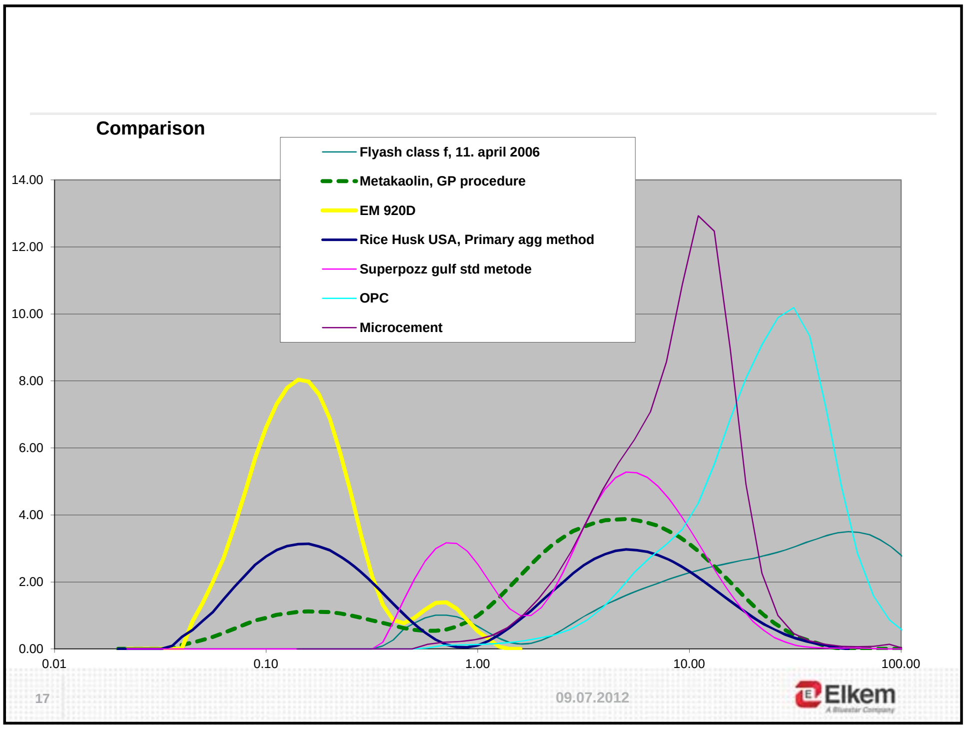
Comparison
Flyash class f, 11. april 2006
Metakaolin, GP procedure
EM 920D
Rice Husk USA, Primary agg method
Superpozz gulf std metode
OPC
Microcement
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0.01
0.10
1.00
10.00
100.00
17
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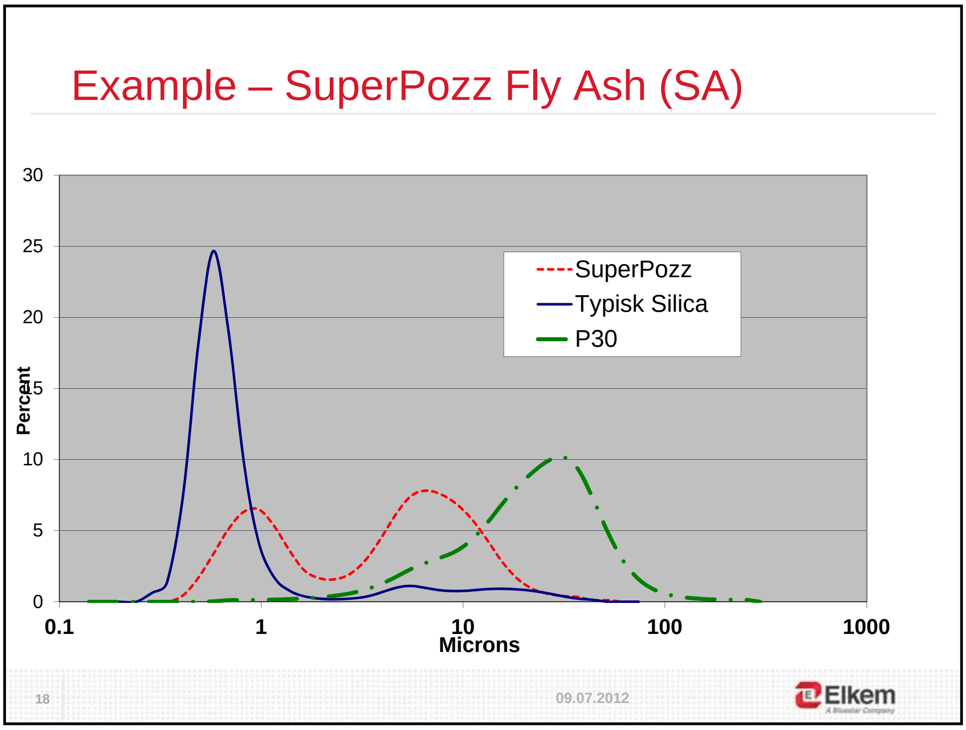
Example – SuperPozz Fly Ash (SA)
SuperPozz
Typisk Silica
P30
Percent
30
25
20
15
10
5
0
0.1
1
10
100
1000
Microns
18
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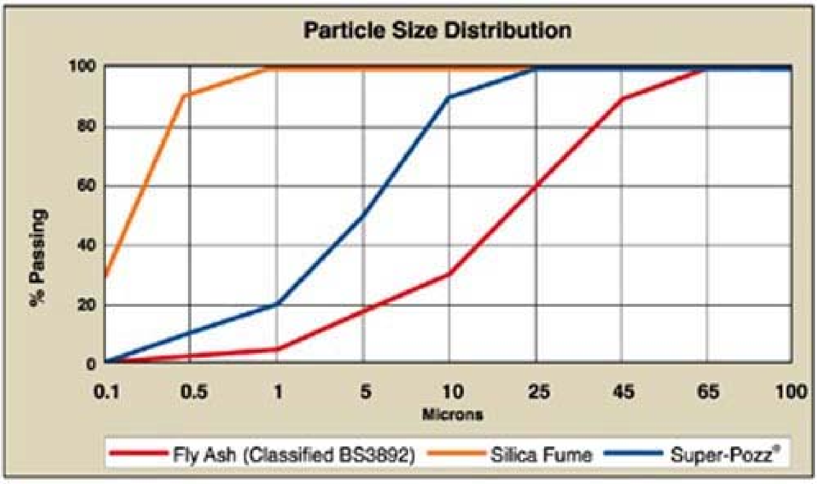
Manufacturers numbers



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Superpozz

- Pozzolanaktivitet:
  - Sammenligning mellom referansemørtel og mørtel der 10 prosent sement er byttet ut med testmaterialet.
  - 7 døgn: 94.3%
  - 28 døgn: 103.6%
- ”Effektivitetsfaktor” er ca. 1

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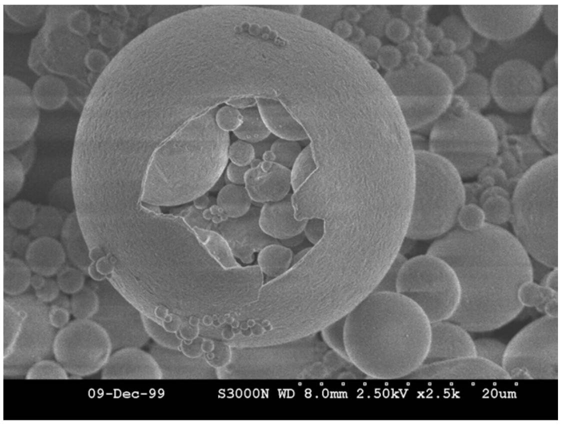
Superpozz



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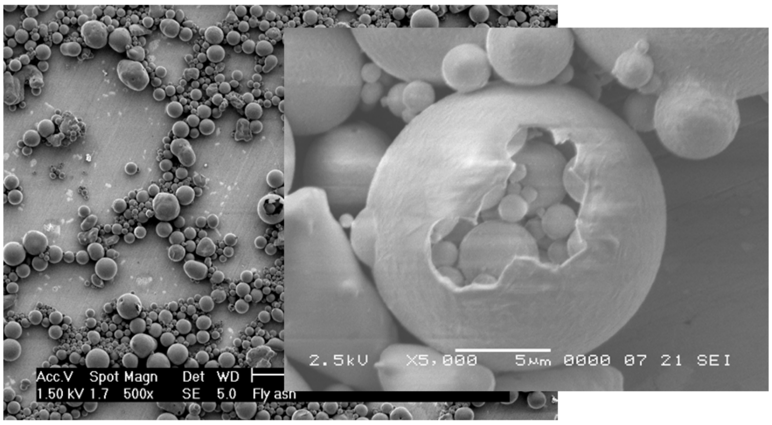
Superpozz



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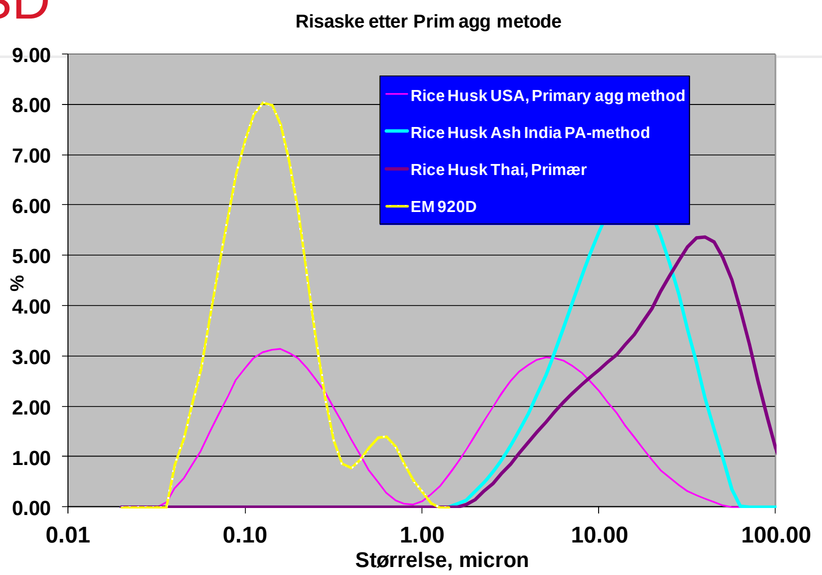
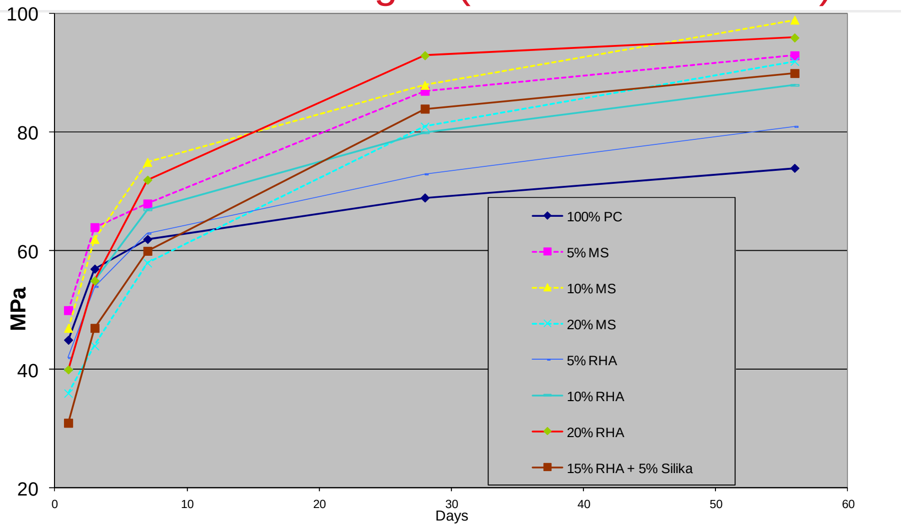
RRHA

- + 600 million tons of rice
- 125 million tons Rice Husks
- + 25 million tons RRHA if burnt properly
  - Pre-treatment
  - Burning temperature
  - Post-treatment

PSD



RRHA/MS – strength (Material from USA)



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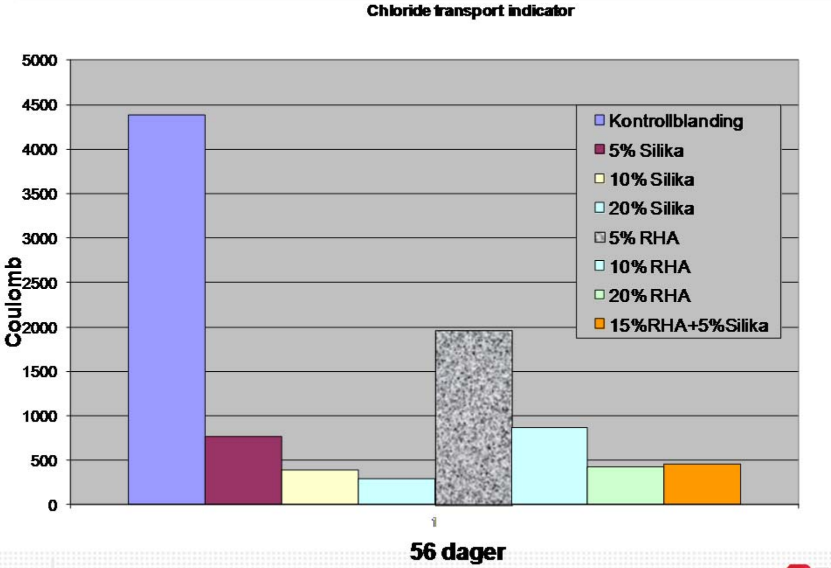
RRHA – Chloride indicator



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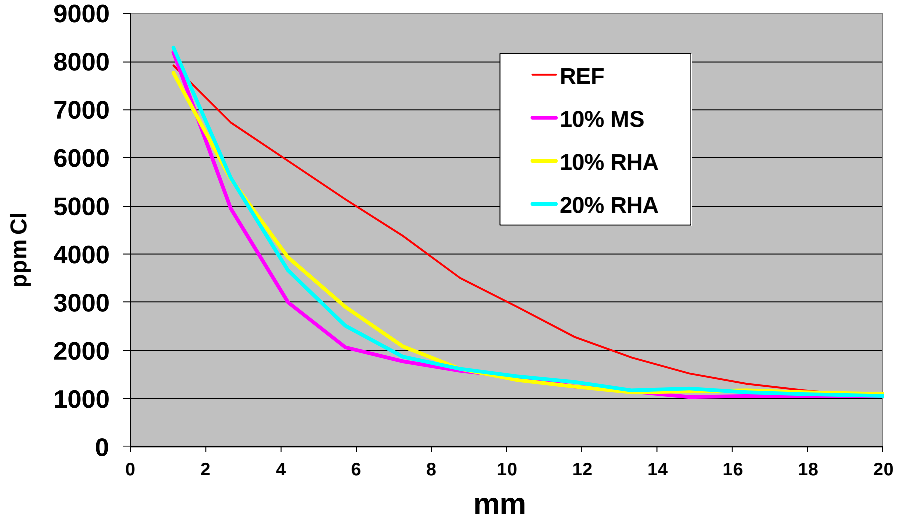
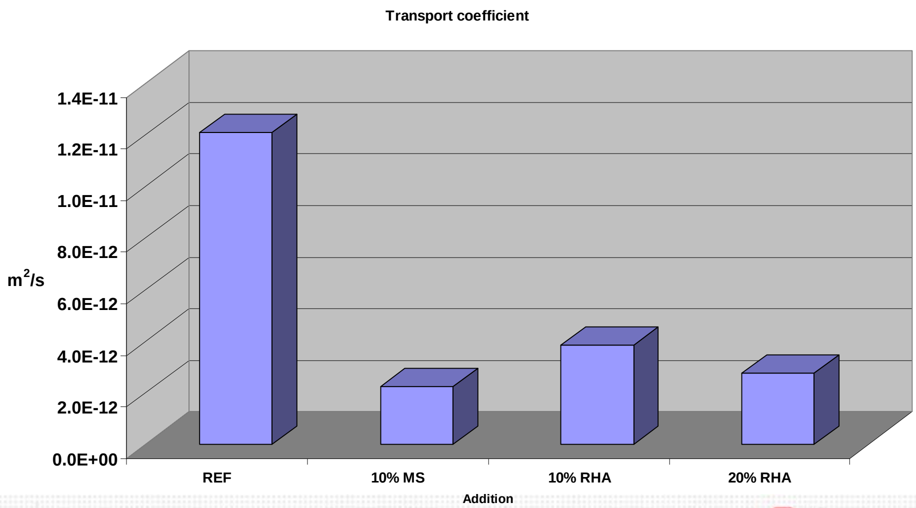
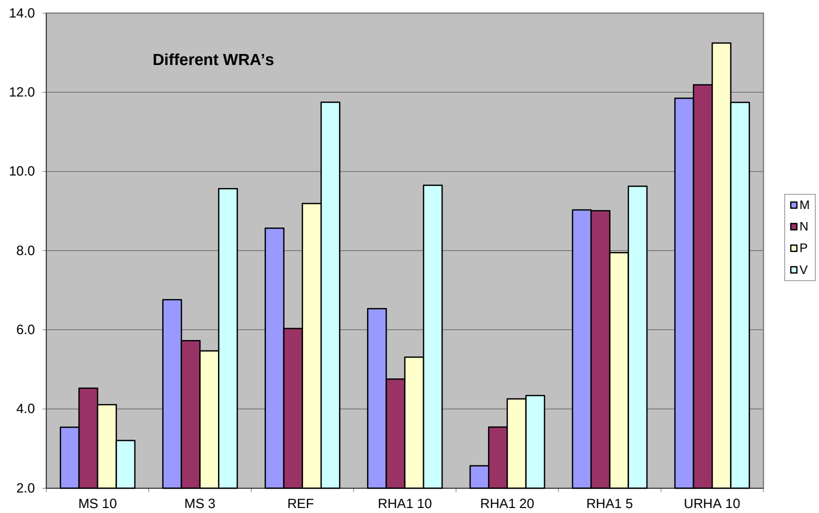
Chloride Profiles



Transport coefficient



Transport coefficient NTBuild 492



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Mix ID	Average Adjusted Charge, Coulombs	
Ref	4185	
	3599	
10% MS	472	
	429	
10% RHA	833	
	859	
20% RHA	487	
	494	

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Perlite performance

Tests at University of Toronto

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A Bluestar Company

Mixtures

- White Cement Control
- 10% Perlite A
- 20% Perlite A
- 10% Perlite B
- 20% Perlite B
- 15% Perlite A plus 5% silica fume
- 10% silica fume

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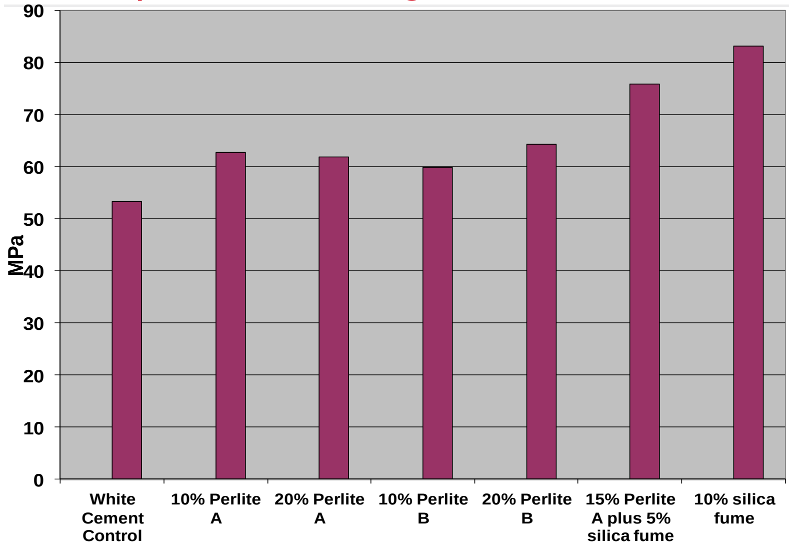
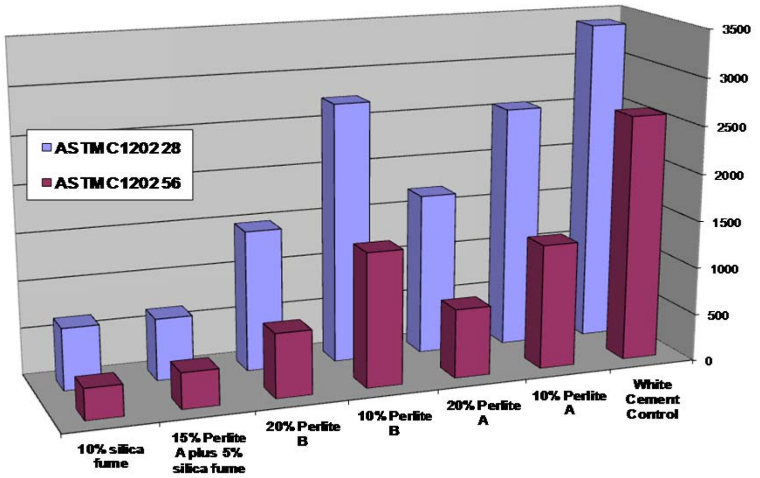
Tests

- ASR – C1567
- Strength
- C1202
- C1556

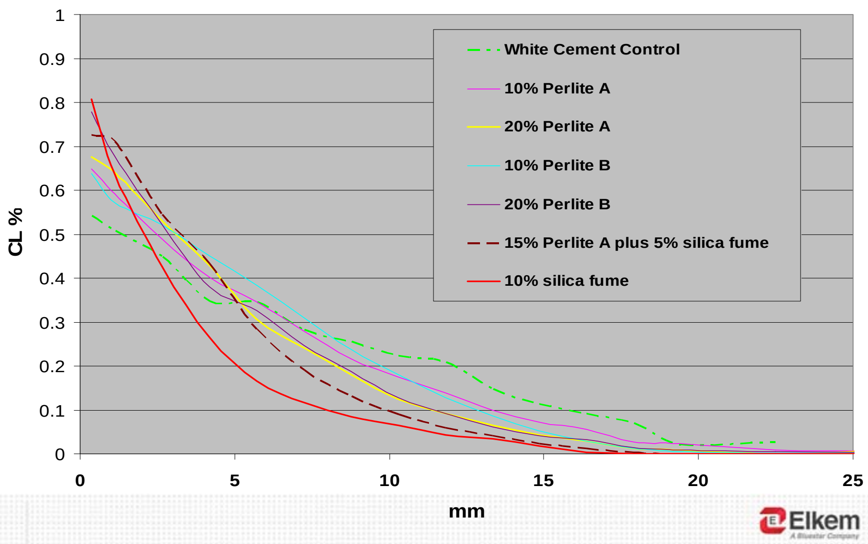
Compressive strength



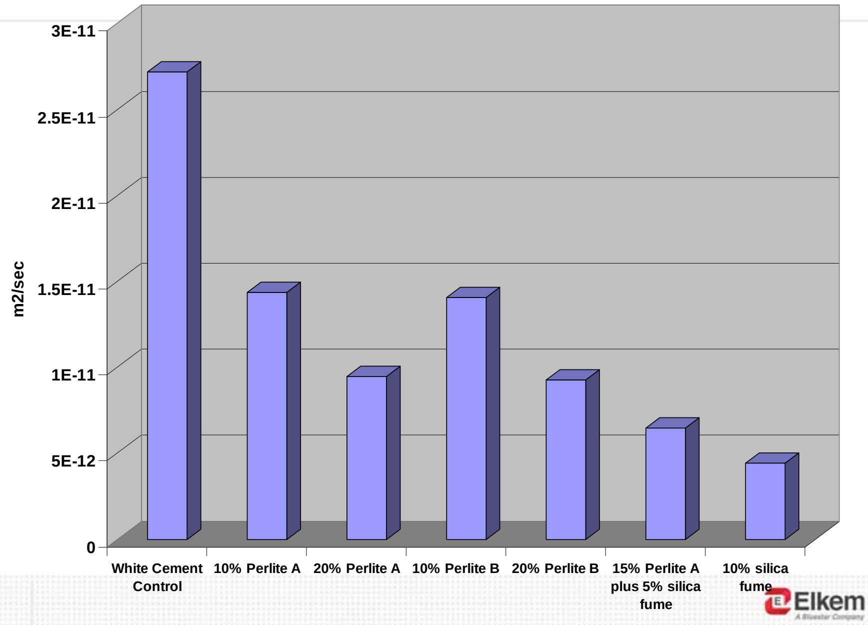
ASTM C1202 – Perlite fines



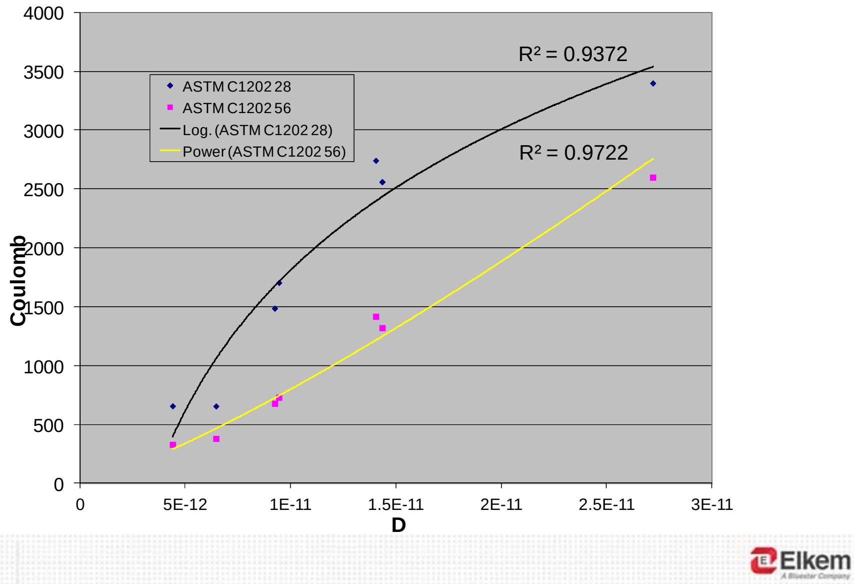
Chloride profiles, Perlite



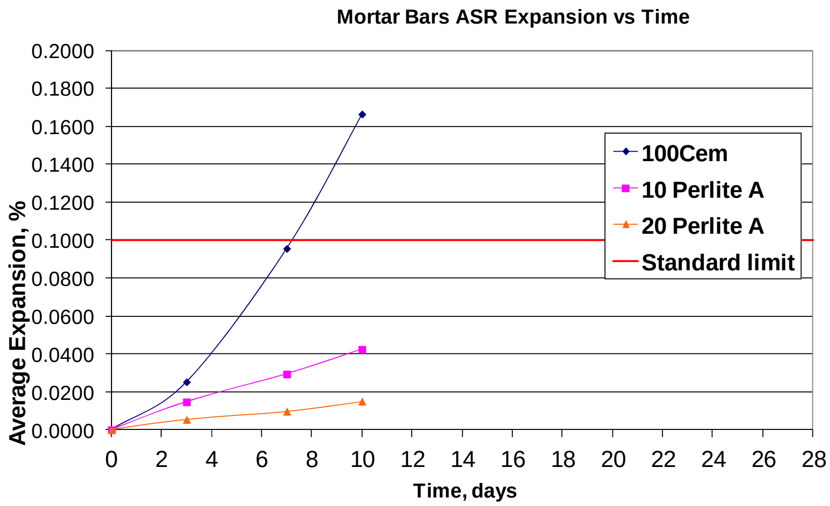
Diffusion coefficients



Coulomb versus D_{eff}



Perlite - ASR intermediate result (U-Toronto)



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Current work

- Ashes from “other combustions”
  - Burner technologies
  - Pre/post-processing
- Influence of particle sizes and distribution
  - Milling technologies
    - PSD-shape and parameters
    - Economy
- HVFAC in ternary blends

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HVFAC

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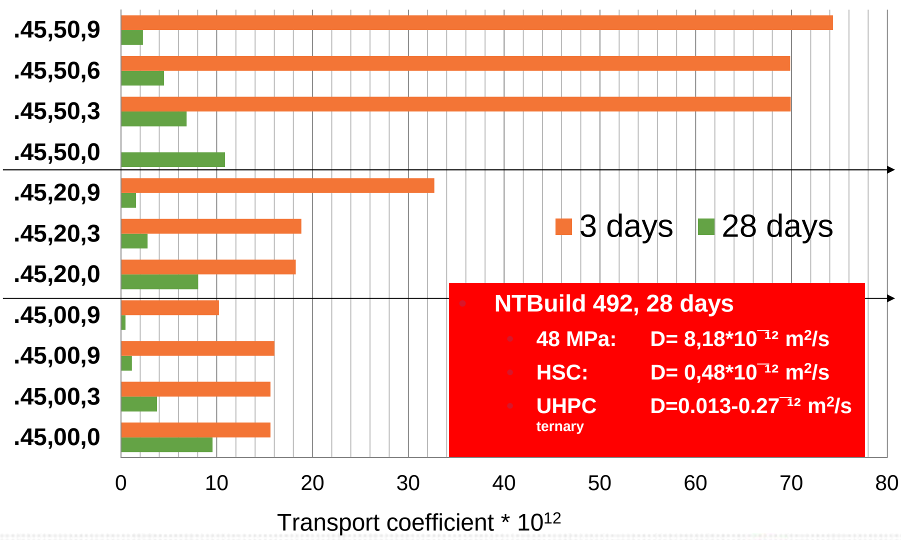
Chloride Transport, NTBuild 492



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The future?

- Fly Ash is the only SCM voluminous enough to have an impact
- Which way will fly ash production go?
  - Will quality change?
- Will the 6-10% growth in annual cement consumtion continue to grow?
  - How long?
- Will there be sufficient raw materials?
  - For cement
  - For aggregates
- Will other binders be needed – in large volumes?
  - Documentation lacking
  - Portland based for critical structures – here experience exists

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ISSN: 1893-1162